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Evaluating Identification and Sorting Technologies for Improved Ferrous and Non-Ferrous Recycling

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By

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A DISSERTATION

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Ph.D. DEGREE DISSERTATION

The Ph.D. Degree Dissertation of Leslie Brooks has been examined and approved by the dissertation committee as satisfactory for the dissertation requirement for the Ph.D. degree in Sustainability

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Abstract

Metals recycling is one of the oldest industries in the United States that now employs over 530,000 individuals. It has always played a significant role in the economy, contributing $109.78 billion to the US economy in 2018. Furthermore, recycling supplies extensive goods and services, the Institute of Scrap Recycling Industries (ISRI) reported that every year greater than 900M Mt of scrap (~2 billion pounds) are consumed by manufactures globally, equating to 40% of the raw material demand. Additionally, as climate change becomes a greater threat, we must seek practices to lessen our carbon footprint, and recycling helps to reduce the environmental impact of metal production. Relying on this industry as an alternative to make-take-waste habits, means understanding how the industry's efficiency is being challenged by growing feed volumes of diverse, complex product designs. This work details the internal and external factors that impact the development of ferrous and nonferrous recycling operations. This knowledge is then applied to design and perform an extensive "true to yard" analysis with technologies that have potential for addressing inbound inspection and material identification challenges. These results allowed us to understand the limitations that would arise when attempting their deployment at material handling facilities, and then use these factors to build a model capable of quantifying and comparing these techniques, which is not available in previous literature.

Inbound inspection and material identification are critical; they are the first opportunity once material is received to prevent comingling, downcycling, and contamination. Scrap yards identify and sort specific alloys from large quantities of mixed metals by means of visual and cognitive recognition with the aid of a few standard tools (a magnet, file, acids, and/or grinding wheel). This work tested handheld analyzers (HHs) that utilize x-ray fluorescence (XRF) and laser induced breakdown spectroscopy (LIBS) technology to determine the level of technological assistance they can provide to improving identification during the inspection process. Beforehand, we had a good indication of how HHs perform on material that has clean, smooth, uncoated surfaces (prompt scrap) but, what we aim to find is their response when used on "unprepared materials," like those coming out of stock that are old, used, weathered, and/or warped (obsolete scrap). For these instruments to be deemed useful for inbound inspection/ identification purposes, it is crucial to understand and evaluate their limitations on scrap that is not altered and thus, true to a yard setting. Results indicate that in their current state, HHs can inform and verify content for a significant range of materials. They also show grade matching (identification of an alloy by name) is possible but less likely on unprepared scrap. However, the ability to register and share elemental composition percentages at rapid speeds, allows a trained user to know immediately what contaminants are present, often being high levels of Si and Fe. In addition to understanding how these technologies perform under real world conditions, it is also important to quantify whether their benefits outweigh their costs. This work examined five different scenarios for sorting and identification, each scenario offering different levels of alloy-specific sorting capabilities. The model that was created allowed for return on investment (ROI) comparisons, and evaluated the impacts of different market conditions, changes in volume, volume distribution, and uncertainty. This technoeconomic assessment showed that even a high amount of comingled material can be profitable at high volumes under certain market conditions. Although, comingling led to diminished profits, where segregating proved beneficial even at lower volumes. As we continue to invest, educate, and execute sustainable practices, we must understand that recycling should only come as an attempt <u>after</u> we have exhausted our efforts to reduce and reuse. Moreover, we can work to obtain a better balance along the supply chain by encouraging and creating more practices like design for recycling (DfR) and extended producer responsibility. Being that these behaviors will require a lot of societal reform, we need to ensure that we work to reduce landfill feed by providing the recycling industry with the tools and practices that are effective and efficient at getting materials identified and sorted.

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Glossary of Terms

Acronyms and Abbreviations

ASR	Automotive Shredder Residue
CCD	Charged couple device
COMEX	Commodity Exchange
Cu	Copper
DE-XRT	Dual energy X-ray transmission
EDXRF	Energy dispersive XRF
HH	Handheld
ICP	Inductively Coupled Plasma
IMI	Inbound Material Identification
Laser	Light amplification by stimulated emission of radiation
LIBS	Laser induced breakdown spectroscopy
LME	London Metal Exchange
LOD	Limit of detection
MS	Mass Spectrometry
NF	Non-ferrous
OES	Optical emission spectroscopy
PGNAA	Prompt gamma neutron activation analysis
PMI	Positive material identification
RE	Rare-Earth
SDD	Silicon drift detector
Si -PIN	Silicon drift diode intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region
WDXRF	Wavelength dispersive XRF
XRF	X-ray fluorescence

Metal Abbreviations and Chemical Symbols

Al	Aluminum
B	Boron
Be	Beryllium
CA	Cast Aluminum
C	Carbon
Cu	Copper
CS	Carbon Steel

Fe	Iron
Mo	Molybdenum
Nd	Neodymium
P	Phosphorous
Pb	Lead
RM	Red Metal
S	Sulfur

Sn	Tin
SS	Stainless Steel
V	Vanadium
W	Tungsten
WOA	Wrought Obsolete Aluminum
WPA	Wrought Prompt Aluminum
Zn	Zinc

Chapter 1

A System's Perspective: Understanding the Broader Implications of Recycling

1.1 Introduction to Metals Recycling: A Brief History

Metals recycling first entered the limelight around World War 1, responsible for helping produce weaponry and ammunition due to mass shortages of raw materials (Bradbury, 2017). "Scrapping" of various items by more and more people developed as a result of many trying to survive the economic struggles in the 1930s, including the Great Depression (Bradbury, 2017; "Museum Exhibit Celebrates the History of Scrap Yards | Scrapware," 2020). During the mid-1900s nearly 150,000 scrap processors had developed around the country and further encouragement ensued as manufacturers of the 1960s discovered the value in aluminum products thus, paving the way for a world of recycling that exuded economic opportunity (Bradbury, 2017; *London Metal Exchange: History*, 2020; "Museum Exhibit Celebrates the History of Scrap Yards | Scrapware," 2020). The incentives during the 1970s were undeniable; not only in the US, but around the world, people were recognizing the growing waste problem and the profit to be gained from recycling metals. As scrap yards began to pop up in cities everywhere, competition was on the rise making business fun but challenging. The most successful scrap operations picked niche materials to purchase and then flourished, based on their display of integrity and holding value in mutually beneficial relationships; garnering loyalty from a consistent supplier base, who trusted that honest and fair pricing was being provided by the yard.

1.2 Present-Day

The current picture of the industry is painted differently. There are now several large companies that have dominated the industry which allows them to influence pricing outside of what is indicated by the market (Brooks et al., 2019). Larger, well-established companies can attract customers by paying higher prices for materials that are not necessarily a reflection of what they are worth (because they have the ability to offset it with larger profit margins on other items and/or handling of much higher volumes). Consequently, finding niche markets isn't enough of a competitive edge. Scrap yards must be capable of managing large influxes of new materials and alloys if they are to stay afloat. In other words, one must be willing to accept a wider range of materials to keep suppliers from seeking out alternative options, and as the volumes of more unfamiliar materials increases, so do the risks involved. These risks can lead to sizable losses, the kind that might be a setback to a larger company but the demise of a developing one. Furthermore, as the industry becomes more competitive, valuing quality and loyalty comes second to prioritizing the conveniences of one-stop-shops and seeking best pricing and higher profits. Why is this significant? As stated by Cliff Humphrey in The Better Earth, a report on Ecology Action, "capitalism is predicated on money and growth, and when you're only interested to maximize profits, you maximize pollution (Roberts, 1970)." This industry is in a state of constant flux, which makes having consistent (or standard) operating processes difficult. Every pound of material that enters the yard *must be* evaluated as unique and subjected to thorough inspection. The key is being equipped with tools that promote the yard's ability to be prepared and adaptable, because without them, money and time are in many cases saved by doing what is easier and not what is best. In this era, the significance of limiting the volume of materials being trucked to landfills is prodigious. We must take a closer look at the inner challenges of these industry processes if we are to push for incentives that facilitate quality and improved recycling efforts, especially if the alternative is throwing away resources because of the relatively cheap costs to landfill (Seldman, 2018).

1.3 Motivation and Objective

Recycling has long been revered as the answer to coping with an unyielding accumulation of *waste*, a direct result of a profligate linear economy model. Yes, reduce and reuse are ideal starting places, but the reality is in only a little more than a quarter century our population has doubled, and there is no current system in place for micromanaging people's consumption. When it is clear we can't rely on preventative measures to address this pressing issue, we are left with mitigation—recycling being the front-runner. Inbound inspection and material identification are critical processes that require attention and improvement in ferrous and nonferrous recycling. They are the first opportunity, once material is received, to prevent comingling, downcycling, and contamination. One of the most noteworthy contributions from recycling is that it reduces our dependence on and need for raw primary extraction of ore (Geyer et al., 2016). If we do not focus on the challenges recyclers are facing when attempting to identify and sort these materials, it will result in increased usage of practices like downcycling and comingling. This will lead to the accumulation of impurities, necessitating dilution largely obtained through use of primary materials. Consequently, this then offsets the positive environmental contributions we seek from the recycling process. A reduction in goods produced predominantly of virgin materials directly conserves land and resources, reduces emissions by requiring an average of 60% but upwards of 95% (for metal) less energy to produce, and reinforces a transition to a more circular economy (EIA, 2021). Obtained from the Bureau of International Recycling (BIR), Table 1.1 below shows the magnitude of savings from production with secondary materials as opposed to primary (*Bureau of International Recycling*, 2018). Furthermore, in the wake of the Intergovernmental Panel on Climate Change's (IPCC) 2018 release, *Global Warming of 1.5°C*, which states the need for a 45% reduction in CO_2 emissions globally (from 2010 levels) by 2030 and net zero by 2050, it is imperative we recognize how much we rely on the efficiency of the recycling process to help achieve said goals (*IPCC, 2018: Summary for*

Policymakers, 2020). The discussion concerning improving recycling rates/ waste management vs. maximizing scrap utilization rates, are not one in the same; the former involves collection while the latter production. We must promote looking at recycling from a systems perspective and begin to understand that only by addressing these aspects in concert with one another will we be able to improve and maximize the efficiency and effectiveness of the recycling industry.

CO2 Footprint & Savings (Kilotonnes of CO2/100,000 Tonnes (Bir.org)

Material	Primary	Secondary	Savings/ 100,000 Tonnes	% Savings	Energy Savings
Aluminum	383	29	354	92%	95
Copper	125	44	81	65%	85
Ferrous	167	70	97	58%	74
Lead	163	2	161	99%	65

Table 1.1 Emissions generated from creating products using primary materials vs. secondary materials (*Bureau of International Recycling*, 2018).

1.4 Novelty and Research Questions

In order to achieve an authentic systems perspective, the first step must be to provide key insights into an industry that's complexity cannot be known nor understood from the outside looking in; largely because there isn't any literature that offers an in-depth review from someone who has worked in the field and can speak to the full scope of challenges that exist. Large companies may offer handbooks to new employees but texts like these are confidential and often won't cover aspects that management doesn't believe are relevant to that job title. Generally, they provide an overview of the different types of metal that the company will and won't accept into the yard, and some tips for helping to identify those metals. After addressing this gap of knowledge on industry processes for metals recycling operations, next we must bridge the gap between technology development and industry conditions. To do this, we will need to provide an assessment of what the industry requires of technology and why it's so difficult to achieve, and then complement this evaluation with a comprehensive list of the technologies that are being developed and what they offer to different parts of the industry. This will help to reveal how, where, and why identification and sorting technologies are lacking and why it is crucial we remedy this. Subsequently, an experiment testing some of the leading identification technology on actual scrap metal will need to take place, allowing us to truly learn the extent of what identification technology can provide and current limitations. This is another novel area to shine light on because manufacturers are not completely transparent when advertising their products, and much of what is shared pertains to new production scrap and not the old, rugged, dirty scrap (obsolete) that is the most difficult to identify. Lastly, we must attempt to calculate the value we gain from making these improvements – economically and environmentally. A techno-economic assessment quantifying the costs of the several variables involved in determining whether to comingle/downcycle as opposed to performing an alloy-specific sort, could expose how beneficial upgrading technologies are (i.e. technologies that contribute to cleaner commodity streams), and incentivize yards to invest in them. These gaps in and lack of knowledge must be addressed if we are to support and provide for this industry what it needs to take on the role we now demand from it.

Central Question 1: What influences industry processes and what challenges can be addressed or improved?

- What does the industry look like? Who are the stakeholders involved?
- What are the everyday challenges to recycling from consumer to producer?
- What are the supply and demand implications for scrap?
- What processes do materials go through? Where do they end up and how do they get there?
- What does technology development for this industry look like and what type of aid are they providing?

Central Question 2: Why is identification and proper sorting during inbound inspection critical and can technology help improve it?

- What are the risks of incorrect identification/ why is technology for identification significant?
- How are materials characterized currently and what are the current processes for different metal groups?
- What do we need from technology to help improve identification?
- What role can handheld analyzers play when it comes to satisfying these needs?

Central Question 3: Under what conditions are technologies that upgrade metals to produce cleaner streams economically feasible?

- What are materials being bought as vs. how they are being sold? What complications arise and what value is being lost or could be gained?
- What parameters must we understand, and which variables do we need to quantify?
- What do different levels of technology offer and how do they vary in their capacities and deployment?

Chapter 2

Ferrous and Nonferrous Recycling: Challenges and Potential Technology Solutions

2.1 Introduction

The way we manage 'waste' directly impacts our ability to achieve a more circular economy and fundamentally shapes the future of our planet. Ideally, this would begin with shifting what we perceive to be 'waste,' and eliminating the throwaway mentality while replacing it with a reduce and reuse one. At present, infrastructure does not support this type of extreme societal shift, leaving recycling as our leading alternative. Recycling diverts end-of-life products from landfills to be re-processed into usable products, ultimately reducing the extraction of primary materials and thus, conserving energy and resources. The Environmental Protection Agency (EPA) estimates that 75% of the United States' waste is recyclable and currently we recycle about 30% (EPA, 2021). A multitude of factors play a role in low recycling rates, part of which being insufficient information about the inner workings of the systems tasked with managing our recyclables. Therefore, progress can be achieved by expanding knowledge in areas that impact technology development, consumer participation, and the efficiency of operations for those facilities involved. This work specifically focuses on the undertakings of ferrous and nonferrous scrap recycling yards, the challenges of operating, and the present state and complexities of technology development.

2.2 Industry-Wide Challenges

Daily, individual yards responsible for managing end-of-life materials are met with many challenges that can cause large fluctuations in how things operate and how decisions are made. Although these challenges can be complicated, unpredictable, time consuming, and costly, yards must find ways to manage them effectively regardless. Particularly problematic and straining for recyclers are environmental, health and safety regulations, commodity market volatility, technology limitations, and logistics. Competition and conflicting motivations of participants are additional variables that often disrupt business fluidity. Economic opportunity and an effective, efficient operation stem from recyclers being knowledgeable in and understanding these industry aspects.

Scrap industry structure and competition

According to the U.S. Census Bureau, there are over 8,000 facilities operating in the U.S. (as of 2017). This number includes processors and brokers who either directly collect or facilitate the collection and purchase of scrap from industrial and/or commercial accounts, and/or from individuals (typically referred to in the industry as ''peddlers''). Apart from brokers, these facilities are responsible for separating scrap into distinct commodities, most of which are defined by the Institute of Scrap Recycling Industries (ISRI) in their Scrap Specification Circular. It is unlikely to find any two yards that are identical. They range in what materials they receive and their volumes; this is primarily dictated by their location and will influence how and what processes take place. Dependent on what metals a particular facility accumulates, materials are shipped export, and/or domestically to a steel mill, shredding plant, aluminum/non-ferrous secondary smelter, and/or another type of secondary metal scrap processer such as a granulator (wire chopper). “Feeder yards,” facilities that accumulate much smaller volumes but are still responsible for separating and processing material, are also prevalent in this industry. These yards will typically send mixed loads (multiple commodities separated but on a single truck) to higher volume yards where the material is then combined and sent to the types of facilities previously stated.

Competition among scrap yard facilities comes in many forms and has been on the rise for quite some time. Although it is common for startups to emerge, the chance of thriving in this industry is contingent upon whether market conditions are optimal and if the owners are well versed in the industry components outlined herein. Often, startups come in with aggressive purchase prices that they cannot necessarily match with adequate sales prices. These types of non-market driven actions lead customers to believe that their scrap is worth more than its actual value and feel taken advantage of if another yard offers a lower price. Not only is this a nuisance to preexisting yards’ business, either forcing them to pay more (even if not economical) for plant feed to keep their customers, or risk losing feed suppliers, but it can also sully a yard or even the industry’s reputation. Albeit there are instances where new competition discovers niche markets for commodities and can support aggressive buying.

In previous years, scrap yards were mostly family-owned and operated businesses that developed their customer base from relationships grounded in exceptional customer service, loyalty, honesty, and fairness. For much of the 21st century however, large companies that own many of their own feeder yards have not only impacted how business is done but, in many cases, what businesses will survive. Regardless of yard size or type, ever-thinning margins that have stemmed from rising operating costs, have forced many to prioritize things like easy in-and-out business, fast payment terms, best price despite weight, and places that can act as a “one-stop shop.” These tactics aren’t highly profitable for the yards, but this is the type of service customers prefer. When you can’t cut costs, or find other areas to increase profits, then you need to be handling large volumes to offset these now smaller profit margins. Yards adjusting their business to meet the demands of and keep their customers is not unforeseen. However, the material handling challenges that have come as a result are new and often unpredictable, and addressing them requires unique, innovative solutions.

Stringent environmental, human health and safety regulations

Environmental, human health and safety regulations are imperative but demanding on recycling operations. Operating in this line of work means regularly encountering large, sharp metals, hazardous materials, and heavy machinery. According to ISRI, the industry currently provides jobs [directly and indirectly] to 534,506 workers (Institute for Scrap Recycling Industries (ISRI), 2020). The scrap industry ranks above the national average when it comes to injuries and illnesses per year (Rosengren, 2016). Additionally, employees are not the only ones at risk; people living near yards, truck drivers, and customers/peddlers also incur risk. The surrounding environment and a considerable amount of people can be impacted by recycling operations which is why compliance plays a significant role, and regulations exist on local, state, and federal levels. Some of the federal environmental regulations yards are controlled by include The Clean Air Act (CAA), Clean Water Act (CWA), Resource Conservation and Recovery Act (RCRA), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and The Toxic Substance Control Act (TSCA) (Wagger, 2013). These laws impact nearly every aspect of the business, from being permitted to operate and where, to how materials are handled and what is accepted. Moreover, deciding to accept a wider range of materials, which many yards must do to stay competitive, directly correlates to additional regulations, some requiring large upfront mitigation costs. Enforcement of these regulations comes with a zero-forgiveness policy and fines for noncompliance start as high as $37,500/day (Wagger, 2013); this doesn't include the potential costs of mitigating the negative public relations that can accompany such violations.

Markets

Commodity markets can be extremely volatile. They can fluctuate unexpectedly and not necessarily in response to 'typical' supply and demand expectations. China, being the largest net importer of scrap materials from the U.S. for example, has a significant impact on the U.S. recycling industry, particularly when it comes to pricing, and how, when, and what scrap commodities are acceptable to ship (Salidjanova et al., 2017). Under the Trump administration for instance, when negative relations impacted trade with China, it was estimated that the U.S. would be required to redirect over 700,000 metric tons of material (by 2019) (Rosengren, 2018). Not only is the volume alarming but redirecting the materials the U.S. commonly exports to developing countries is incredibly tough because they are some of the most challenging scrap types: highly co-mingled (unsorted) and often with high levels of contamination. An unexpected upside to lessening our ability to export such materials, however, is recognition by the National Recycling Coalition (NRC) and others in the industry, that a nationwide effort to reform the recycling process is necessary. Thus, aiming to rid the occurrence of comingling, and urging "cleaner streams" in municipal solid waste (MSW) and scrap metal recycling ("National Recycling Coalition comments on "China Crisis"," 2018). Outside of markets, there are other factors that can influence the value of materials, such as inconsistent domestic buyers and sellers. They may not necessarily alter the market per se, but they can impact commodity pricing through random delayed or aggressive buying. In some cases, this leads to yards having to sit on material or when feasible, sell at an alternative price to a different end user; this may also result in an altered product of potentially lesser quality. Because of this, attempting to determine how to process and price materials, while already working on very small profit margins, can be extremely difficult and delicate for buyers and sellers.

Logistics

Materials have several different forms to which they can be packaged for transport (e.g. baled, boxed, loose), all dependent on whether it is being transported by rail, shipping lines, truck, or some combination. The mode(s) by which material is transported (often decided by the purchaser) dictates how the load is packaged and handled, how much of the material can be loaded, and finally, how it will be priced. Seventy percent of freight is presently moved by trucking (Bartheld, 2015); tractor-trailer trucking comes in a number of forms: flatbed, van-trailer, roll-off/open top container, export container, etc. All of these have varying weight limits, require different equipment to load many of them, and some are more difficult to load than others. Having the correct equipment for loading and unloading is essential because trucks are expected to be weighed in, emptied, and weighed out relatively quickly. Often, scrap companies do not have their own fleet of trucks and transportation must be outsourced. Truckers get paid by mileage not by the hour, and if a yard does not have an efficient process, requiring that some trucks wait extended periods of time to be loaded /unloaded, the trucking company might refuse to work with them in the future (Sandoval, 2001). Not having the right equipment can also lead to damaged trucks and trailers (which may be owned by a third party) when loading and unloading. Furthermore, yards must be diligent about having a clear/clean pathway for trucks as to avoid flat tires, which can be especially difficult when most of the material moving through a yard is capable of causing such damage. If any of these become common occurrences, not only are repairs costly but business may be lost. Aside from the magnitude of obstacles to overcome once a truck is on site, it is important to point out that the act of scheduling trucks can be particularly challenging as well, for availability can be limited. Although there are hundreds of thousands of trucking firms, that doesn’t mean they have large fleets and that all trucks in their fleet are operational (due to repairs or a shortage in drivers) (Sandoval, 2001). Other logistic considerations include route optimization and being sure to meet particular weight and height limits for different roadways.

Technology

Previous generations of recyclers operated during a time when standard tools and equipment could effectively help with sorting, identifying, processing, and moving materials. However, the growing complexity of product design combined with an increased volume of materials entering recycling facilities has introduced challenges which now require innovative, strategic technological assistance. Technology development for this industry is challenging because not only are there many different types, sizes, shapes, and forms of materials, but they are typically mixed, and non-metallics are often comingled. When materials arrive at processing facilities, aside from 'peddler scrap,' they are received in truck-load quantities ranging from a few thousand pounds to upwards of 44k lbs. After the vehicle's gross weight is recorded and a photo of the load is taken, the yard is expected to dump, identify, sort, transfer the material, record an empty vehicle weight, weigh sorted commodities on a separate scale (when applicable), make deductions/upgrades, and provide payment all within minutes of the arrival time. This is the bare minimum that happens for every load that crosses the scale, and shipments are being received one after another, non-stop during all business hours. As a result, the types of technologies needed for improvements are wide ranging and must be industry specific to fit in with the flow of operations. Another requirement of technologies if they are to be successful and penetrate the market, is that they must be affordable and deliver a quick return on investment (ROI). Additions to currently owned equipment are typically preferred over the high costs to install entirely new equipment. Other considerations for new technologies include tools that can aid in inbound inspection, improved safety, and the additional processing required to sell to a smelter or mill (e.g. size reduction, material liberation, lifting, transporting, and confirmed positive material identification).

Incentives

An underlying impact on the recycling system that can be influenced but not controlled, are the varying motivations of companies and customers (i.e. what drives individuals to participate). A company incentivized by large profits may behave differently than one who prioritizes being environmentally conscious. These differences can drastically impact business decisions from how a facility chooses to sort different commodities to the amount of comingling and contamination. This is the same with customers; some may value reducing costs, saving time, or having an environmental commitment. It will be these values that determine how and in what condition materials are delivered to the yards. The social component of sustainability is typically the hardest to address and that's why understanding what incentivizes people is part of the solution to making positive changes in this industry. We must have ongoing conversations around how to make the process easier for customers and work to be transparent about the intrinsic value of their recyclables. Companies need to network and communicate with other yards and researchers to spread awareness while also educating themselves and their customers. If we are to achieve real system improvements and integrate technology that is affordable and can improve the shipped product, this type of information exchange must always be occurring and encouraged.

2.3 Yard Operations' Challenges

Industry-wide challenges are unavoidable and where economic opportunity for recyclers can be limited, but having strategic, innovative solutions to the challenges that are presented in this section are where facilities can find opportunities to distinguish themselves. Scrap recyclers work on extremely small margins which means even the slightest errors can have big impacts. Inbound inspection, identification, contaminant removal, sorting, communication, and training are all processes that make or break an operation. Discovering solutions and developing technology that can be aimed toward improving these processes, means understanding how they fit into the bigger picture and the day-to-day struggles yards must confront.

Material identification, processing, and sorting

Inbound material identification (IMI) is what takes place when material crosses the scale and enters the yard. This point in the identification process is going to define what you will pay the seller and subsequently, the category it will be inventoried under in "volume received." Positive material identification (PMI) on the other hand, is the ability to positively confirm the chemical composition of a metal or alloy; this type of identification is preferably occurring simultaneously. These two forms of identification, although sounding seemingly similar, are very different and a large part of why keeping inventory in this industry can get chaotic. IMI is what the material is when it hits the scale, PMI is what it can become. For instance, if a customer enters the yard with a box of mixed, clean aluminum, the yard could buy it in as "Mixed Low Copper" or "MLC;" this is an aluminum package (with low copper content) defined by ISRI's Scrap Specification Circular as a mix of 1xxx, 3xxx, 5xxx, and 6xxx series aluminum. This can be sold as an MLC, but, with enough training, or advanced technology, you can sort out some of the specific aluminum alloys such as 5052 or 6063. By doing this, you are making a more specific package that is likely marketable to more buyers at a higher price than you would get for selling a mixed package; this is an example of how yards can create economic opportunity for themselves.

However, identification of any sort is a persistent challenge in the metals secondary industry, and incorrect identification costs scrap processors money and time. The MLC example previously given is a mixed package that was created because the ability to distinguish similar looking metals can be very limited, therefore, a specific commodity package was made to allow and expect a degree of comingling. This saves yards time as it has reduced the level of involvement required to sort out every specific alloy.

In this case, the commodity package prioritizes the guarantee of a low overall copper content, there are other commodities that necessitate an entirely homogenous chemistry. When metals are mixed unknowingly or dense materials are identified incorrectly, for instance discovering the copper that was purchased is truly copper-cladded steel, the yard's bottom line suffers. Once the customer is paid, the transaction is considered complete. Consequently, this error generates a direct financial loss that the yard must absorb, as there is no way to make up the price difference between copper at $4.00/lb and steel at $0.10/lb. Even occurrences where the difference is only a few cents, purchasing thousands to hundreds of thousands of pounds of material means those pennies add up quickly and the result is diminished profits.

To become an experienced scrap inspector, you must spend many years in the yard, physically handling the material. Over time, this hands-on experience allows an individual to learn how to identify metals based on their knowledge of the metal's application and an evaluation of its density (heft). Additionally, during the learning process yard personnel are introduced to standard tools that can expose physical properties that are characteristic of specific metals. Such tools consist of a magnet, file/knife, various acids, and a grinding wheel (spark test). The extent of this identification enables them to at the very least separate out Al + Mg alloys, ferrous steel, cast iron, stainless steel, Zn alloys, brasses, and bronzes from one another. In the past, these tools have been enough to separate scrap effectively and efficiently, but the increasing complexity of alloy design and usage, coupled with growing volumes makes these tools less than adequate. Figure 1 is a simplified flowchart created to illustrate the time and effort required to identify solely the major alloying element (in the absence of characterization and sensing technologies). The red boxes are the extent of IMI that can be achieved given the standard tests denoted by the blue boxes. The starred yellow boxes following the red boxes are opportunities for further verification using acids. Acid testing is far less common, but it is a means that yards have been able to use to assist in some level of identification. As previously stated, observing the density of the material in question (how heavy the material feels) is a method that can be used. This is not included in the diagram but would be noticeable to someone trying to distinguish lead (Pb) from other metals, or zinc (Zn) alloys from aluminum (Al). To determine the trace elements that are present requires a more extensive analysis with specific acids but even once detected (if at all), you will not be able to determine the percentage of the elemental composition it possesses. Certainty of specific alloys cannot be determined with standard tools– it is only with knowledge of the metal's application that one would be able to deduce the likeliest alloy. Elemental analyzers based on x-ray fluorescence (XRF) and laser induced breakdown spectroscopy (LIBS) may have potential for mitigating this issue and are discussed in more detail in the technology assessments section.

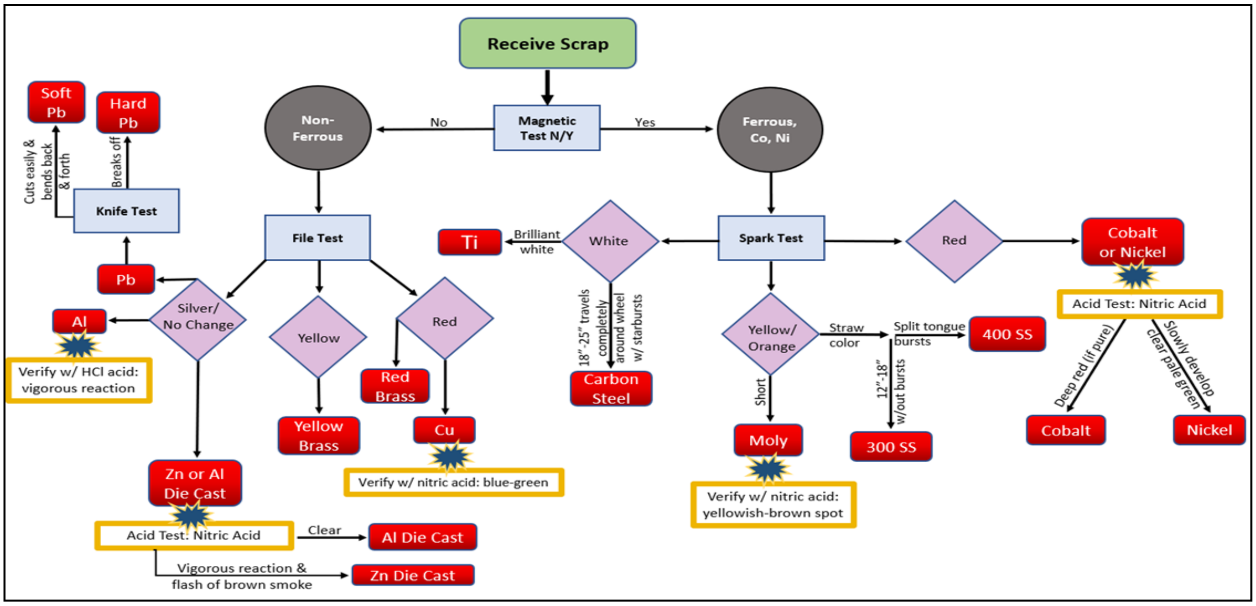


Figure 2.1 Above is a flowchart demonstrating what level of identification standard tools (that lack advanced technology) can provide.

As alluded above, the way material is identified or the form of which it is bought may end the transaction with the seller, but it is not the end of what material undergoes before it can be shipped. Identification is just the prelude to the several processing and sorting steps to follow. Preparing material to ship, whether it is specific to a secondary producer's needs (e.g. mill or foundry) or to ISRI scrap specifications, is often an iterative process. Depending on how material comes in and in what volume, the process can be simple or quite involved. Loads can come across the scale loose, mixed, stacked on pallets, in gaylord boxes or super sacks, baled, shrink wrapped, etc. No matter how the material is contained it needs to be inspected and separated, and therefore must be unpackaged and/or, dumped, and bales should be broken open. Having the material loose and spread out is the most efficient means of checking for and removing contamination, as well as determining whether the material can be upgraded, and which materials need to be further processed to meet specifications. This involves but is not limited to size reduction to below the maximum permitted piece size, removal of non-homogenous attachments (metallics or non-metallics that make the piece not a uniform metal), and PMI confirmation. If liberation of materials and/or upgrades take place, the broken-down pieces will need to be separated, weighed, transferred, and inventoried with the new material it has now become. Scenarios involving single loads requiring multiple steps of processing, sorting, transferring, and upgrades of different materials are common. A load of steel for instance, will be weighed and then emptied on the dumping floor. A lifting magnet is used to pull the ferrous metals from the pile, leaving behind liquids, non-metallics, and non-ferrous metal pieces. The remaining nonferrous could be grouped ''as is'' but if market conditions are favorable and time and equipment are available, there is potential for metals to be upgraded. Examples of these cases would be turning a #2 copper into a #1 copper by shearing off a soldered joint or taking ‘‘irony/dirty aluminum extrusions” and transforming them into a clean 6063 alloy by removing a weather-strip and a few screws.

There are many difficulties presented in processing and upgrading scrap especially when you factor in time as a variable and needing appropriate tools to accomplish said tasks. Equally challenging is being able to track these undertakings actively and accurately, for the action of manual processing inherently requires material to be handled multiple times and often by multiple people. Furthermore, if the market is volatile, pricing and processing can make sense when the material is delivered but may possibly not be economically feasible tomorrow and, in some instances, drastic changes can happen within the same day.

Contamination and deductions

Opportunities for upgrades are one reason yards inspect, identify, sort, and process materials, but avoiding the hazards and downstream impacts of contamination are the true driving force behind many of these processes. Although upgrades provide opportunity to increase profit margins that can be beneficial to the yard, impacts from contamination can generate costly outcomes that can be detrimental. Contamination must be reduced to below the defined specification level or eliminated completely as to prevent the accumulation of impurities, equipment failure or catastrophic events like fires and explosions. Contamination comes in many forms, and it can occur before it reaches the yard, within the yard itself and/or at the facility next in line to receive the material (secondary processor or producer). It can be as simple as non-metallics such as dirt, moisture, oils, concrete, paper, wood, and plastics to more serious things like radioactive contaminants. Furthermore, what is considered contamination depends on the specification of the category of inbound scrap. Say the yard receives a load of source-segregated scrap of a specific alloy, any other alloy or material would be considered a contaminant if it was mixed in at any point. In receiving mixed metal loads, the yards typically can assume that at least 1% of the total volume is non-metallic contamination. This may not seem like a lot, but when you calculate that number over hundreds of thousands of tons, it becomes substantial. Either these losses are figured into the price ahead of time so that yards can afford the costs of proper disposal or time to sort and “clean up” materials, or it is inspected before payment is issued and excess contamination can be deducted and sent back to the supplier. It cannot be emphasized enough just how difficult it is to look at a load that is still in its container and make an accurate quantification of the proportion of contaminants; in this form inspectors are restricted from seeing what is in the middle or the bottom of the pile. Sorting piece by piece is truly the only way to be certain what contamination exists, but fast, frenetic operations don’t usually allow for this meticulousness. All too often inbound loads are combined with similar feed material from other sources without thorough inspection and only the visual estimate of contamination from the top view of the load is relied upon. Sometimes the load is sampled, and that sample is completed separated and then used to estimate the quantity of contaminants for the entire load. Some of the larger scrap metal sorting plants that have suppliers with established supply records will pre-process each specific type of scrap from the given supplier separately through what is known as a ‘‘wash plant.” It is designed as part of a process to remove most of the non-metallic contaminants from a load, then proceed to sample and hand-sort the wash plant output. This allows the purchaser to get a good estimate of both the metallic recovery as well as the metal composition, which they then use to determine the price of the supplier’s scrap; usually there is a fee associated with this level of pre-processing. This arrangement works well but requires regular, high volume deliveries provided by the supplier and mutual trust. This arrangement is not applicable to the front-line scrap yards often supplied by a large sum of occasional peddlers who deliver small quantities and prefer immediate payment. Attempting to quantify and handle contamination is a costly endeavor. This could be directly, by finding a large quantity of lesser value material, or negative value material such as moisture, dirt, foreign material, or attachments mixed in and having paid for the entire volume all at the higher value commodity price, or by the time it takes to sort, process, and remove the contamination.

Managing and handling contamination is a vital part of operations for quality control but also for safety, economic, and environmental reasons. Yard fires are a very serious problem that result from and/or spread due to contaminants not being eliminated during inbound inspection. In 2017, an estimated 1,500+ fires took place at processing facilities in the U.S. and there are cases of prior year’s experiencing more than double that (Fogelman, 2018). Yard fires produce serious consequences costing not only millions of dollars in clean-up, downtime, and repairs but it can also cost lives (Fogelman, 2018). Metal scrap is hard to burn, what typically ignites are organic contaminants such as oils, paper, cardboard, rags, plastic and wood. Quantification, proper handling and disposal of contaminants, and proper deductions for their presence in the inbound feedstock is the key to safety, environmental compliance and the economic bottom line of any scrap yard. Reducing the frequency and likelihood of these occurrences will be a significant stride forward for the industry.

Training and communication barriers

The only standard operating procedures (SOPs) that exist in this industry are ones relating to safety. How to keep yourself and others safe in a yard setting is taught and required primarily through Occupational Safety and Health Administration (OSHA) training. Although expectations of how to perform tasks safely is defined, it is the duty of operation managers to reinforce and make “yard-specific.”

Training labor for operating stationary and mobile equipment is detailed and well-defined. Common yard equipment such as forklifts, front loaders, alligator shears, etc. have manuals with specific instructions and most equipment will also be accompanied by hours of use and safety training. Operating the equipment for different materials is not straight-forward however, and manuals do not exist for those tasked with inspecting, identifying, and sorting. This industry not having SOPs isn't for lack of trying, it is because every load needs to be treated as unique. The guiding force for how tasks are performed is safety, everything else requires imaginative, quick, on your feet thinking. Thus, knowing how and being well-prepared to execute these tasks is directly tied to the number of hours spent in the yard, physically performing them; learning is hands on, and repetition based. Considering how much time one needs to be able to perform their job with confidence and absent of constant supervision, employers are making a big investment every time they hire a novice. It takes most beginners at least 6 months to begin to recognize what a given metal is without help and with cognitive certainty. This is not an expectation that can be had moving forward if product designs are changing and alloy diversity is increasing. Making cognitive recognition more challenging will only increase the training period, and not only for those that are new. The physical and mental demands of this type of work, and the time involved to be efficient at it is a central area that must be fully comprehended for useful technology in this area to exist. Technology developed from these considerations, in the hands of someone who is trained how to use it, could reduce training times required for material identification confirmation. It is also important to consider that the time it takes to train someone costs money and there is no guarantee that workers will not take their skills elsewhere once they have acquired them.

Communication cannot be sparse at any stage of operations. It is everyone's job to make sure what they are communicating is clear and understood by the receiving party. Lines of communication are constantly crossing within and throughout company departments. Communication lines cross in the yard amongst employees whilst directing in-yard traffic to equipment operators, and to non-employees like truck drivers, instructing them where to go. A lot of communication is happening between buyers and sellers before the material even arrives at the yard. Good communication, aside from being the principal ingredient to safety in the workplace, is the way mutually beneficial relationships are developed and sustained. Misunderstandings lead to mistrust between buyer and seller and there are several opportunities for information exchange to go poorly. Suppliers may request a price for a particular item they intend to deliver and arrive at the yard with something different; this can be a genuine mistake or an intentional act in attempt to receive better pricing. A large barrier to communication in this industry are inconsistent meanings for various terminology. There can be multiple names used to describe the same thing or one of those names could mean something very different to a particular buyer/seller. For instance, ‘‘dirty aluminum” to some means aluminum with iron attachments and maybe even a specific (max/min) percentage of iron is expected, but to others it might mean that it has plastic or excessive oil/grease. This dilemma partly stems from a widely varying supplier base, which is why most yards require that for materials to be priced, they must be accompanied by pictures prior to shipments and/or account managers are sent to perform an in-person evaluation. Before materials enter the yard, much could have changed between then and the time of the inspection, consequently pricing is always subject to change. The strongest relationships are built between parties that understand this reality and thus, effectively communicate any changes, and why or how they can do better moving forward. Although the aforementioned ISRI Scrap Specifications Circular defines different ferrous and nonferrous scrap commodity categories, and provides guidelines for what is acceptable contamination, this is language mostly understood from yard to yard, not known nor applicable to many industrial, commercial, and peddler accounts.

Inventory

It is improbable that inbound volume will ever match outbound volume for ferrous and nonferrous recyclers. Inventory is a constant struggle to track because, as stated in the section on material identification, sorting, and processing, materials rarely leave the yard in the condition or as the commodity of which they were purchased. Not to mention, it is understood and accepted by all those managing these types of yards, that every time something must be touched whether for upgrades, contamination removal, or relocation, there is a fraction of a percent inevitably lost. As continually emphasized, handling thousands of tonnes of material means fractions like these will add up eventually. Additionally, the section on contamination communicates how prevalent contaminants are and how difficult they can be to quantify prior to being dumped and spread apart. Moreover, seasonal changes in the form of increased rain and/or snow can impact how difficult it is to manage, measure, and see contaminants. Moisture in the scrap metal adds a significant variable to the inbound scale weight of any material and if it isn't caught and/or communicated, the impacts can be detrimental to the bottom line. It is understood by recyclers that inventories will have fluctuations in volume from inbound to outbound, but they can often see where it has been redistributed or lost; large volumes that are missing and can't be explained can lead to panic and concerns of theft.

2.4 Technology Assessments

Research and expert solicitation were utilized to prepare the following technology assessments. The result of this investigative work includes material characterization and sensing techniques, in addition to separating and sorting technologies that are or have been utilized in the industry thus far. The information that is provided consists of a description of the technology, the materials it can be applied to, pros and limitations of its application, as well as representative vendors.

Material identification and sorting technologies

As stated, material identification and separation are crucial ingredients to preventing comingling, reducing contamination, and creating economic opportunity. This section provides an overview of several common techniques for metal analysis that contribute to/aid in IMI and/or PMI, either by way of an x-ray-based instrument, the formation of a plasma, or by neutron activation. Many of these techniques have been incorporated into sensing technology and sorting systems which will be presented in the following sections.

Non-Destructive Methods

Radiation/x-ray detectors

A radiation detection system can detect and locate nuclear or radioactive materials. Radiation detectors passively monitor ionizing radiation in the form of gamma rays, or x-rays in a Geiger counter type ionization chamber, or by way of scintillator crystals. In more sophisticated systems, measurement of the gamma or x-ray energy provides information of the nuclear event that generated the detected photon. In the typical flow of checkpoint traffic, these systems are capable of scanning more than 150 vehicles per hour (Liu et al., 2008). Additionally, they have sensitive radiation detection with a very low false alarm rate and quick data integration and display. When installing the detectors, it is important to keep in mind variations in truck sizes as to avoid a case in which the truck is too large to pass through. Example vendors include: Leidos, Inc., Rapiscan Systems, RadComm.

Dual energy x-ray transmission (DE-XRT)

DE-XRT sensors are universally used for airport luggage inspection and medical applications, the main difference being the data processing and image analysis software. A DE-XRT sensor provides an image of the materials, and the color and intensity that are displayed give a relationship between the atomic number and the inspected material. The high density or high atomic number metals (atomic number 26 and higher) have a high transmission damping that shows up darker in the image compared to the low-density metals (atomic number 13 and lower). The material shape and size can also be determined from the image. Metal recyclers can use DE-XRT sensors in belt type particle sorters to separate light metal scrap particles (Al and Mg) from dense nonferrous metals (Zn, Cu, Brass), as well as being able to sort out metallics from non-metallics in things like automotive shredder residue (ASR). DE-XRT technology is unique in that it is not interrupted or highly affected by surface contamination however, current commercial sensors do not have sufficient resolution to distinguish between the dense metals or their alloys, or between the light metals and their alloys. Tomra and Steinert are some well-known vendors of DE-XRT sensors.

X-ray fluorescence (XRF)

X-ray fluorescence spectroscopy is a two-step process that begins with the removal of an inner shell electron of an atom, making the atom unstable. The second step is then filling this vacancy. As an electron transitions from an outer shell orbital to replace the vacancy within the inner shell, it is accompanied by the emission of a fluorescent photon, which holds characteristics specific to particular elements. The energy produced throughout this process provides qualitative information concerning the elements' identity. The amount of energy lost during the transition is equal to the distance between the orbital shells (Bruker, 2021); this amount can be measured to represent the concentration of the elements present. The energetic x-ray spectrum can penetrate through a considerable depth of material, and that depth increases with the x-ray photon energy. This is used in x-ray transmission imaging. In terms of electromagnetic radiation, standard x-ray spectrometers will utilize a wavelength region from about 0.1–11 nm (Blitz).

X-ray fluorescence instruments are either energy dispersive x-ray fluorescence (EDXRF) or wavelength dispersive (WDXRF) spectrometers (Marguí & Grieken, 2013). They have been commercialized in both handheld elemental analyzers (HHs) and in belt type particle sorters. As HH analyzers' capabilities continue to improve, and their prices decrease, they can become more widely used in scrap yards for manual alloy identification. EDXRF sensor particle sorters have also been commercialized to find copper meatball contaminants in the ferrous shred product of steel shredder plants. They have the potential to replace manual picking from the main product stream or from the 'reject stream' of the ballistic magnetic separator. Although XRF is a beneficial tool for elemental analysis and alloy identification it does have some limitations. Technology is continuously being developed to improve XRF's lower precision for and difficulty in detecting light elements as well as improving read times to obtain quicker PMI. There are also extra safety precautions that must be taken when dealing with such instruments for as mentioned, they do emit radiation. Manufactures for handhelds include, but are not limited to, Olympus, Oxford Instruments, Bruker, and SciAps. Tomra and Spectramet are known vendors for EDXRF sensor particle sorters.

IR and NIR spectroscopy

Near-infrared (NIR) and infrared (IR) spectroscopy are absorption methods involving wavelength regions that extend the region of visible light to longer wavelengths and smaller frequencies/energies (Crocombe, 2018). Infrared radiation excites vibrational and rotational motions in molecules. Except for the differences in the energy transfer from the radiation to the molecule, the principles of IR spectroscopy are the same as those of UV–Vis spectroscopy or other spectroscopic techniques. The absorption of infrared light is characterized by the Bouger- Lambert-Beer Law

(Kleinschmidt, 2000). Desktop IR spectrometers identify plastics in 5 seconds. Accuracy depends on quality and completeness of the reference spectra library.

Prompt gamma neutron activation analysis (PGNAA)

In the Prompt Gamma Neutron Activation Analysis (PGNAA) technique, the elemental concentration of the sample is determined from the intensity of the prompt gamma-rays emitted by the sample due to its irradiation with neutrons (Lindstrom, 1993). The nuclei of some elements of a sample placed in a field of neutrons absorb neutrons and are transformed to an isotope of a higher mass number. Conventional neutron activation analysis applies the emitted during the decay of radioactive products for elemental analysis (Gesing & Wolanski, 2001). Some elements do not produce radioactive capture products but do emit prompt gamma rays at the time of neutron capture. If the sample is placed in an external neutron beam from a reactor and viewed by a high-resolution gamma-ray spectrometer, these gamma rays allow qualitative identification and quantitative analysis of the neutron-capturing elements present in the sample (Gesing & Wolanski, 2001). The neutrons do not interact with electron shells and the probability of their capture by the nuclei is small; they can penetrate through a large depth of metal scrap. The energetic MeV characteristic gamma rays can escape from the full depth of the scrap layer conveyed on the belt. This permits 100% analysis of all material in the stream, eliminating the representative sampling issues [expert solicitation]. While the neutron capture and the gamma ray emission probabilities vary from element to element, in principle, quantifiable signal can be detected from every element, hydrogen included (Gesing & Wolanski, 2001).

PGNAA sensor systems are well established in the mining industry and are designed to handle high volume flows of material. Real time, full stream, accurate measurement of the conveyed material’s average elemental composition irrespective of particle size and belt speed are possible. When a material stream is determined to be “off-spec” / contaminated, diversion of these segments within the material stream can be achieved. This would make it quite easy to stage mill feed material by composition/purity. This process could be utilized to improve melt quality and decrease cost by preemptively diverting “off-spec” loads. Gamma Tech has done significant work on the application of PGNAA cross belt analyzers for scrap metal, both ferrous and nonferrous. The first generation of PGNAA cross-belt analyzers were developed with radioisotope neutron sources like decays to produce a slowly decreasing flux of neutrons. Newly developed deuterium tritium Californium, which continuously fusion neutron sources are now beginning to be deployed in PGNAA sensors for cross-belt analyzers. Their neutron flux is electrically controlled and can be turned off when the analyzer is not in-use. They are priced to be cost competitive with Californium radioisotopes and have a potential for future price reductions. Vendors that continue to work on incorporating PGNAA technology into applications for scrap processing and identification include Thermo Scientific, Gamma Tech, Sodern, PAN Analytical, and Gradel Fustion.

Quasi-Non Destructive Methods

Optical emission spectroscopy (OES)

The data obtained by optical emission spectroscopy (OES) contains a large amount of information. The position of each spectrum line gives important information on the chemical composition of the plasma whereas their relative intensity informs us on the energy distribution between the various species in the plasma (Bengtson et al., 2017). OES relies on the detection of photons which are emitted during the de-excitation of the energetic particles in the plasma. Since the length of time associated with de-excitation energy transitions are very short, it is possible to obtain time resolved measurements down to the nanosecond when using equipment with a sufficiently high sensitivity. OES can be utilized in various forms. For example, a plasma can be generated by microwave excitation as in induced coupled plasma (ICP) OES, where the sample dissolved in acid is injected into the plasma generator (Bengtson et al., 2017). ICP-OES is among the most precise and accurate primary quantitative elemental analytical methods. In the case of arc spark-OES, an electric arc is used to melt, vaporize, and ionize a small sample of the metal alloy. The plasma emission is then analyzed by OES. Arc spark-OES is the standard industrial analytical method for elemental analysis of metal alloys (Bengtson et al., 2017; Noll et al., 2018).

Laser induced breakdown spectroscopy (LIBS)

Laser induced breakdown spectroscopy (LIBS) is another form of OES that is becoming more and more popular. The technology incorporates a pulsed, focused laser that generates a high temperature plasma while vaporizing a small amount of material, then the emitted spectra of the plasma is translated to material identification (Musazzi et al., 2014). A portion of the light emitted by the excited atomic and ionic species in the plasma is then collected and spectrally analyzed to determine the sample elemental composition (Bengtson et al., 2017). Quantitative LIBS analysis can also be performed when the assumptions of local thermal equilibrium (LTE) and optically thin plasma are satisfied (Anabitarte et al., 2012)

This technique offers the ability to perform real-time, in-situ analysis as well as a quasi-non-destructive and micro-analysis characterization (Bengtson et al., 2017). Studies often suggest that there is little to no sample preparation needed, however, the small laser focus makes the analysis sensitive to surface contamination and microstructural inhomogeneity. LIBS is considered a surface technique because unlike the varying penetration depth of XRF, pulse lasers can only penetrate a very small distance into the surface of a metal. Unless laser ablation precleaning is incorporated in the analyzer, which adds additional time to the analysis, scrap that is not free of water, lubricants, paint, and other coatings will report inaccurate and/or less precise measurements. LIBS technology is said to have the potential to measure all elements of the periodic table although, it does struggle with Pb alloys, and refractory metals (e.g. W, Cr, Ti). A LIBS sensor has been industrially implemented by Huron Valley Steel (Belleville, MI) on a belt type particle sorter for Al alloy batching from scrap Al, and a commercial version has been under development by Tomra for some time [expert solicitation]. However, there has yet to be a full-scale particle sorter system commercially available in the general marketplace. LIBS based HH elemental analyzers have been recently commercialized by several manufacturers such as Rigaku, SciAps, and TSI Inc.

Diversion and separation technologies

Diversion, and separation technologies primarily involve the 'piece and particle stream' once material has been purchased into a metals processing facility. These techniques are capable of separating strictly by the metal type (ferrous, nonferrous, and/or color but not by alloy), and have the ability to sort out nonmetal (e.g. plastics, foam, wood) from metal.

In contrast with identification techniques, piece/particle sorting technologies are not just one component, they are a combination of a moving particle line singulation or monolayer presentation system, sensor(s) measuring the particle property(ies), and a diversion system. Systems that utilize a combination of different sensors can achieve impressive selectivity and property resolution.

Physical Diversion

Conveyors and diversion

A stacking conveyor pivots about its tail pulley allowing its head pulley to deliver the output to a selected storage bin. Combining with a PGNAA cross belt analyzer would enable scrap composition-based batching in an electric arc furnace (EAF) steel mill. In this application, the maximum piece length is ~1.2 m. A flip chute does not target individual particles, rather it diverts a defined portion of a stream that contains unwanted impurities or directs a stream of a particular composition or other characteristics to a selected output stream. This is a suitable solution to use with PGNAA cross belt analyzers, which do not have sufficient resolution to target individual scrap pieces but do provide accurate average stream elemental composition results. In this application, the maximum piece length is ~300 mm, which does not make it optimal for large throughput. Typically, this method is used for large particle, low volume applications and for laboratory proof-of-concept systems.

Electromagnetically or pneumatically activated paddles rotate into the in-flight particle monolayer, diverting selected particles out of the particle stream. Paddle diverters compete with blow bars in belt particle sorters for handling of larger particles (~7–30 cm), however, it is not suited to handle particles >1 kg. Eriez is a manufacturer known to produce paddle diverters.

An excavator arm mounted grapple is essentially a pick and place device under the control of a skilled operator. It can handle loads of several tonnes and maximum piece sizes of 2–3 m. Mounting of the appropriate sensors on the excavator arm could significantly improve the sorting capability of the grapple. For example, a color CCTV camera and a suitable flood lighting system could be used to improve the operator's view of the scrap piece(s) being handled. Providing this system with artificial intelligence (AI) recognition software could allow it to tell the operator in real-time what it is that's being handled and where to put it.

Air separation and blow bars

Air flow can separate materials by density, size, and shape. Another means for air separation that is useful, includes air circulation through a hammer mill which helps remove a significant portion of light fluff (i.e. foams, textiles, paper, foils). Additionally, conveyor belt systems use suction nozzles to pull off light-weight fluff from the hammer mill output. Vertical air separation systems feed scrap through a zig-zag column with air pushing upwards; heavier metals are collected at the bottom and other materials are pushed through feeds further up. A cyclone separator uses centrifugal force of a spinning air vortex to separate entrained lightweight particles from the air-fluff stream. Blow bars consist of a row of closely spaced high pressure air nozzles that are activated just at the right time, blowing selected pieces out of an in-flight particle stream. Typically blow bars are located near the head pulley of a sorting belt or near the end of a sorting chute. Each blow bar is coupled with a single output chute. Up to three blow bars have been assembled on a single particle sorter allowing separation of the input stream into upwards of four output streams, blowing out one particle at a time. These systems can have very fast sorting belts, with speeds of up to 3 m/s. Blow bar individual particle diverters are popular for color sorters, ECC metal detector sorters, DEXRT sorters, and XRF sorters. Blow bars are nearly universally used in industries for diversion of either belt or chute type sensor-based particle sorters. In general, air separation techniques are considered mature industrial, low-cost technology solutions.

Field/Force-Based Diversion

Electrostatic separators

Electrostatic separators are used to separate conductive products from non-conductive ones. The metal mixture to be separated is introduced via a vibrating conveyor to a rotating earthed metal drum and transported to the area of a corona electrode. Here, the material is electrostatically charged with up to 35,000 volts. Conductive materials (metals) give up their charge very quickly to the drum and are ejected by the rotating movement. The non-conductive materials, however, lose their charge very slowly, and remain adhered to the surface of the metal drum until later brushed off. This allows the material to be separated into a conductive and a non-conductive fraction. The ideal material stream for this method would be a conductive/nonconductive mixture of fines, between 1 mm and 8 mm, dry (surface moisture < 0.2%), completely liberated mono-material particles and be predominantly dust-free. Electrostatic separators are an efficient way to regain valuable metals by pulling out nonmetals or to rid nonmetals from metal parts before further processing. It is a dry separation process capable of delivering high metal purities and optimal for fine metal particles in mixtures of metal and non-conductive materials with high metal content. Typical applications include cable and electronic waste, granulated printed circuit boards, and metal grinding dust. Steel shredder fines and granulated light fractions are predominantly nonmetal and are typically very wet. Electrostatic separators require the material feed be dry. When this is not the case, drying costs have been known to exceed the value of the metal recovered. Therefore, a shredder plant is not a preferred installation for electrostatic separation. Hamos is a known vendor of electrostatic separators.

Eddy current-based metal detectors, sensors, and separators

The utilization of the eddy current is nothing new to those in waste management and recycling, but there are additions that can be made to these systems. One example of this is an eddy current coil metal detector. These metal detectors typically consist of two coils: an emission coil that generates an alternating or pulse magnetic field and a detection coil that detects them. Any metal that is in the magnetic field changes the magnetic circuit impedance and generates an output signal proportional to the metal particle size and conductivity. Metal detectors can be installed on residue conveyor belts to monitor and quantify the amount of metal lost to the landfill, and to signify need for process corrections required to eliminate these losses. Furthermore, an array of small eddy current coil metal detectors can be used as a sensor for a metal sorter, separating residual metal from the eddy current rotor (ECR) sorter residue stream to create *zurik*, a nonferrous scrap package with a high percentage by volume of stainless steel (SS). Some of these sensors can locate the metal pieces on the sorting belt and distinguish between diamagnetic (e.g. Al, Cu, brass and Zn) and paramagnetic (e.g. SS) metal pieces by analyzing the phase shift between the emitted and received alternating magnetic field signal. With diamagnetic metals, the received signal leads, but for paramagnetic metals, the received signal lags. In this group of technologies, differences in scrap particle properties generates a difference in the force on the particle that automatically directs the particle either over or under the splitter. Typically, these are binary separations, but in some cases a split into three streams can be achieved.

Although such technology has high throughput capability and typically low cost, a major limitation of the current metal detectors that exist on the market is that they are only counting the number of metal pieces above the threshold size. There is however a potential for developing detectors that estimate the quantity of metal lost by considering the size of the individual signal pulses, and differentiating between diamagnetic nonferrous, paramagnetic stainless steel, and ferromagnetic steel.

Vendors of eddy current coil-based metal detectors and particle sorters include: Eriez, Tomra, Steinert, and S + S.

Eddy current rotor separators (ECRs)

When an efficient force separation method is available, typically it is more cost effective than the same separation line with a particle sorter. A strong eddy current force is generated in an electrically conducting particle when it is exposed to a fast-alternating magnetic field. By Lenz's law, eddy current force repels the particle from the source magnetic field. This principle is utilized in eddy current rotor separators (ECRs), which use a fast-spinning roll surfaced with alternating North and South rows of permanent super-magnets to generate the local alternating magnetic field. ECRs utilize an alternating magnetic field that generates eddy currents and electrically conductive particles get repelled from the rotor field ejecting conductive non-ferromagnetic particles. Ferromagnetic attraction dominates the eddy current repulsion and ferrous particles are strongly attracted to the rotor and are spun by the high frequency pole changes, drilling holes in the belt and the rotor shell. Thorough magnetic separation of ferrous particles from the ECR feed is a must.

ECR repulsion is highly dependent on particle size and shape. Different ECR designs are necessary for large and small particles. Closely sized particle feed streams give better results. Some shapes (e.g. wires and foils) fail to be separated out by ECRs that are designed for large particles due to insufficient eddy current generation. Smaller particles need a higher frequency (HF) magnetic field to generate sufficient repulsion. Manufacturers are now marketing HF ECR's specifically designed for metal separation from fines. This then enables additional metal recovery from grit and fines screened from 1 mm to 9 mm. The metal recovered from such grit and fines are mainly cast Al grit and small pieces of Cu wire.

An ECR's splitter can be adjusted for either high product purity or high product recovery. Achievement of both requires ECR separators in series or multiple passes through an ECR separator. ECRs are sometimes operated with two splitters to obtain high purity and high recovery fractions in a single pass through the separator. In general, ECRs separate electrically conductive non-magnetic materials from nonconductive materials. Material recovery facilities (MRFs) use ECRs to separate Al beverage cans from other nonmetallic containers. They are currently used in shredder plants for *zorba* recovery, a nonferrous scrap package high in aluminum content. They are also used in nonferrous metal sorting plants to produce pure *twitch* (Al scrap product). Stainless steel and lead however, are poor electrical conductors and stay in the nonmetallic stream. They can be detected and separated by the eddy current coil sensor-based particle sorters described above.

Magnetic separation

Magnets are one of the most valuable tools when it comes to sorting metals. They are your ‘‘go to” tool for extracting ferrous metals from waste streams by means of magnetic attraction. Although, materials containing iron are more prevalent and of lower value which is why it is essential to be able to extract them from higher value commodities easily; nickel and cobalt are also able to be identified using magnetic forces. Magnets are available in several different configurations. For instance, there are scrap lifting magnet attachments for excavator arms (often in combination with grapples), primary drum magnets separating ferrous shred from the shredder output, over-belt magnets pulling up residual ferrous from nonferrous stream conveyor belt, and magnetic head-pullies pulling down residual ferrous from nonferrous stream conveyor belt head pulley. Additionally, there are secondary drum magnets diverting residual ferrous, pieces with ferrous attachments, and slightly magnetic particles from the nonferrous stream. A magnetic ballistic separator can then use momentum to throw ferrous particles with substantial nonferrous attachments over the splitter, while the magnetic head-pulley pulls the clean ferrous product down short of the splitter. Residual nonferrous and other non-magnetic materials are not affected by the magnetic field of a magnetic ballistic separator and fly over the second splitter. At a shredding plant, a practically automated production of clean ferrous shred can be generated using a magnetic ballistic separator. There can be significant improvements seen in the ferrous shred purity and nearly complete removal of shred pieces with substantial Cu/brass attachments (meatballs). It is a lower cost, higher throughput solution as compared to XRF sensor particle sorters and is usually suggested as a replacement for handpicking in this application. The downfall is that up to 20% of the ferrous in the feed reports to the shredded motors (‘‘meatballs”) output stream; requiring that ferrous be recovered from this stream, while clean nonferrous must then be sorted from the residue stream.

Nearly all these magnetic separator configurations are available with either permanent magnets or electromagnets. In most cases, the permanent magnet units are less expensive to buy, operate and maintain. One can use magnetic separators in these configurations to design simple, low-cost circuits to separate the ferrous portion of most of the ferrous scrap types in scrap yards from the problem impurities such as sand, dirt, rocks, sow, ice, water, and other fluids. Overall, magnets are efficient in separating ferrous from nonferrous content.

Rare-earth (RE) magnet units are capable of separating even slightly magnetic austenitic stainless steel. The introduction of rare earth magnets was a major advancement in magnetic separation techniques because they have much higher magnetic strength than conventional ferrite or ceramic magnets (up to 25 times more pull) yet provide similar circuit stability and long service life. The magnetic strength of the RE magnet falls in the medium– intensity range – 4,000 to 10,000 gauss. Most widely used RE magnets contain an NdFeB intermetallic composition. Properly designed RE magnets also have high magnetic gradients and a significantly amplified holding force. This means they can ‘‘reach out” and attract weakly magnetic or very fine iron contaminants and hold them so tightly that wash–off by-product flow is virtually eliminated. The RE magnetic field strength and reach makes them well-suited for improving the recovery of these types of materials:

1) Steel shred and other particles with attached steel on primary magnet drums
2) Nonferrous particles with steel attachments
3) Weakly magnetic contaminants, such as iron oxide or rust, which do not respond well to conventional ferrite magnets
4) Magnetic separation of paramagnetic stainless steel
5) Conductive nonferrous metal particles by eddy current separators

Although magnets are a powerful tool, they do have limitations. A circuit with a series combination of different magnetic separators is necessary to efficiently separate clean ferrous from pieces with nonferrous attachments, stainless steel, and mildly magnetic iron oxides. Magnetic separators alone cannot effectively separate mixed material assemblies such as cars, white goods, and other mixed obsolete scrap. These need to be shredded and mono-material pieces must be liberated before the clean ferrous fraction is magnetically separated. Vendors that provide magnetic separation solutions include: Eriez, IFE Aufbereitungstechnik GmbH, IMRO, Steinert US, Bunting Magnetics Company, Ohio Magnetics, Recycling Equipment Manufacturing, SGM magnetics, U.S. Shredder and Castings, Walker Magnetics.

Fluid Based Diversion

Fluidized bed sink-float

An inclined vibrating air table fluidizes the low-density particles in the feed stream. These flow down the slope while the dense particles are not fluidized and are conveyed by vibrations up the slope of the table. This is effective for small, close in size particles and is used to separate plastic insulation from chopped copper wire. For fluidized sink-float, the bed of sand is fluidized by the forced airflow where the speed of the airflow controls the density of the sand. Al and Mg floats while Fe, Zn, Cu, and brass sink. Products are separated from the sand by screening. A drawback of this method however, is that hollow shapes get filled with non-fluidized sand and sink regardless of density, reducing the recovery of light products and contaminating dense products.

Heavy media separation

Heavy media separation involves placing mixed materials into a liquid bath of either water having a specific gravity (SG) of 1, water containing a fine suspension of magnetite with an SG of 2, or ferrosilicon (an SG of 4.5 in water). Mixed feed materials used in this method are sized below ~150 mm with ranging densities. The quantity of magnetite or ferrosilicon in suspension is adjusted so that the fluid is in between the specific density of the alloys that are to be sorted. Heavy media is one of the most effective high-volume methods for sorting plastics, wood, and rubber from mixed aluminum. It is also becoming more widely used for sorting nonferrous metals from one another in mixed shredder packages, like zorba and zurik. However, this method is not effective when sorting higher-density alloys, since it is not practical to achieve fluid specific densities in the range of 7.0 g/cc or above. Additionally, there is the issue of added contamination from any dense, hollow, or boat-shaped components for they are likely to float. Furthermore, there is the high cost of maintaining constant density slurries. Some known vendors for heavy media separation include FLSmith Minerals, ESR International, and AD REM.

2.5 Discussion and Future Work

The technology appropriate for a particular metal scrap recycling plant primarily depends on the plant size, its position in the processing chain, material feeds, their volumes, and safety concerns. Technologies that are efficient, safe, affordable, easily integrated, and act as a measure to prevent problems as opposed to merely mitigating them, can spread and become commonplace, as can be seen by the unanimous use of radiation detectors. Yards that receive large volumes of industrial scrap commonly use video cameras to capture images of the load as it is weighed in by the scale operator; this initiates the inbound inspection process. The images taken here and throughout the steps that follow serve as proof of the material's appearance when it was received by the yard. Once the gross weight has been recorded and the material passes through the radiation detection system without issue, the scrap is unloaded and the pile is then visually assessed by an inspector to (1) confirm the scrap category declared by the supplier, (2) qualitatively estimate the proportion of contaminants in the load, and (3) assign the applicable deductions. As loads of industrial scrap are typically compositionally homogenous, any new or unknown delivered materials are identified through sampling of a few pieces. When PMI is regularly required, yards apply laboratory benchtop technology testing (which they either own or outsource). Hand-held elemental analyzers can also be a sufficient means for some degree of positive alloy identification.

Yards that handle considerable amounts of ferrous scrap are likely utilizing a load-cell equipped lifting magnet on the material after it has been dumped as a part of their inbound inspection process. The load-cell data records the ferrous scrap weight, while leaving behind excess moisture, nonferrous metals, and non-metallics on the dumping floor. In some cases, an inbound trailer of presumed ferrous scrap may be unloaded with a lifting magnet leaving the contaminants in the trailer to be returned to the supplier. For shredding plants, the feed is predominantly oversized ferrous steel scrap whereby multi-material assemblies and inbound elemental, or alloy identification are less of an issue. Minimill customers value low amounts of Cu, Ni, and Cr in their shredded, ferrous scrap feed. Getting a good value for the nonferrous metal concentrates is easier when compositions from suppliers are consistent. Alternatively, metal content lost to the nonmetallic residue is both a direct financial loss and an indication of lack of control in the metal recovery and sorting circuit.

The economic feasibility of the technologies discussed and their associated return on investment (ROI), requires a very involved, specific, and technical valuation that will be unique to every yard. There are frameworks that have been developed to estimate ROI for incorporating advanced technology but as of now, they are not comprehensive. These frameworks involve quantitatively structuring material flows and understanding how incoming materials are transformed or upgraded into output grades, that are then transferred and/or sold in the scrap market. Currently, they have yet to consider the necessary supplier base and market conditions needed to support its continued use and lack environmental metrics and comparisons to alternative methods of handling. Supplementary methodologies (e.g. life-cycle assessments) will need to be employed to clearly understand these types of additional aspects. Technological strategies may also lead to enhanced operational strategies like blending algorithms and reverse logistics models.

The more work that is done to understand the past, present, and future challenges of waste management and recycling, the quicker we can arrive at solutions to overcome them. Comingled streams are becoming more prevalent and at a faster rate than the industry has been able to keep pace. This has a lot to do with the fact that technologies being developed for material identification and sorting do not perform on-site as well as they do in theory. The primary reason for this is that they are being designed to perform said function, not said function in relation to their use in scrap yards. In order for instruments and advancements in technology for the secondary metals industry to be widely deployed, they must be designed specifically for use in these types of operations.

The metals recycling industry plays a critical role in the future of sustainable development. It is understood that improving secondary utilization rates will require much more than advancements in technology development; industry-wide cooperation and transparency will also play major roles. Beyond the secondary metal industry, progress can be made through more careful consideration to alloy design, boosting consumer participation, and encouraging extended producer responsibility and design for recycling practices. Reduction in primary extraction, conservation of materials and energy, preservation of land and resources, are just a few of the many reasons we need to prioritize addressing the challenges presented in this work. Fundamentally, if we are to seriously shift worldview to a circular economy approach, we genuinely require a system that can handle and support that shift.

Chapter 3

Potential for X-Ray Fluorescence (XRF) and Laser Induced Breakdown Spectroscopy (LIBS) Handheld Analyzers to Perform Material Characterization in Scrap Yards

3.1 The Scrap Gap: Aligning Expectations with Capabilities

Recycling, as an industry, connects countries through trade relations and largely impacts economic growth (Institute for Scrap Recycling Industries (ISRI), 2020). The monetary gains achieved from developing this industry often overshadow the actual intended purpose of recycling as an action. Financial advantages aside, recycling is how ecosystems, for all living organisms, have had the ability to sustain themselves over time. It is the only means, apart from the impossible feat of eliminating consumption all together, that we have to conserve the planet's non-renewable resources and preserve land—a direct translation to a reduction in energy usage and emissions. The irony is that the systems put in place, the ones we now urgently rely on for managing all of our recycling, were not intended nor built to achieve this. Today, these facilities are often referred to as metal recyclers and/or scrap yards. Originally designed to manage a single type of metal or a specific selection of materials, are now responsible for [but not limited to] shipping, receiving, identifying, sorting, processing, packaging, and inventorying hundreds of thousands of tons of mixed miscellaneous ferrous (metal containing iron) and non-ferrous (copper, aluminum, titanium, etc.) metals globally (Brooks et al., 2019). The scrap that is compiled and moved through these locations, are purchased by secondary processors (mills, refineries, foundries, and/or smelters) according to commodity type. These commodity classifications attempt to regulate an expectation of how material is to be separated and received to ensure not only quality but safety.

In an effort to meet these expectations, a process known as inbound inspection is initiated as soon as materials enter a facility. Most of this process is based on a visual confirmation of the material's identity, which at this point only considers physical properties such as shape, density and/or color— the type of characteristics that could potentially indicate an end use application associated with certain alloys. Having knowledge of the material's application is immensely useful for quick identification (e.g. the majority of windows and door frames are a 6063-aluminum extrusion). If the material is unfamiliar, there are standard tools such as a magnet, file, knife, and/or less common, acids, that can help inform the presence of a particular element, but they don't provide the ability to verify the percent breakdown of the chemical composition (Brooks et al., 2019). Identification based solely on visual inspection has been a fairly effective means for sorting a large percentage of what historically ended up in scrap yards, but this was fundamentally because 1) yards were consistently receiving familiar materials from familiar places, 2) before late, yards could afford to turn materials away and be specialty/niche yards, and 3) an object's application could be associated with a specific alloy.

Innovations of the 21st century have brought on a multitude of new and unexpected challenges for modern day scrap yards. For instance, industrial sectors that are known for producing high scrap volumes, such as transportation, have started using different alloys for like-products, removing the ability to identify based on knowledge of the application. In addition, increased competition has forced yards to accept a wider range of materials whether or not they are well-equipped and educated on how to best handle them. Transitions such as these, have led to an influx of diverse and complex alloys at high volumes further complicating identification during inbound inspection. Moreover, the scrap's condition once received can vary greatly from its original form, another factor that has long challenged the inspection process. Difficulty with identification significantly increases when the scrap being evaluated is obsolete, which is another term for *old* scrap reaching its end of life, that in many cases has been altered from its original form (due to weathering, morphing, accumulating contaminants, etc.) (Blomberg & Söderholm, 2009). Obsolete scrap varies considerably from what is known as *prompt* or *new production scrap*. *Prompt scrap* is the material commonly recovered from somewhere along the manufacturing chain that is likely to have identification attached, and/or be contaminant-free with homogenous surfaces, making it more easily discernable (Blomberg & Söderholm, 2009).

The inability to distinguish between metals and their alloys at this capacity leads to diminished profits as well as comingling and downcycling, both of which result in products of lesser value and the accumulation of tramp elements (Gaustad et al., 2007; Gaustad et al., 2012). What's more, is that these widespride practices force increased dilution of melts with primary metal by secondary producers—essentially exacerbating the buildup of impurities and capping scrap utilization rates (Gaustad et al., 2007; Gaustad et al., 2012; Hatayama et al., 2014; Reuter et al., 2006). Furthermore, incorrect identification followed by improper sorting and separation increases the yard's and the end processor's risk of catastrophes. As of March 2019, fires occurring at these facilities was up 26% from 2017 equating to 1800+ fires occurring across the US and parts of Canada (Fogelman, 2018, 2019). Disastrous events such as these are not only costly to the yard, but they pose environmental and human health costs as well. Yards are the hubs for sorting and decontaminating materials for future processing, the risks are too high for them to lack the requisites to do so.

3.2 Present-Day Characterization for Metal Recyclers

Scrap yards are not void of technology all together and there has been a handful of milestones reached when it comes to material handling and characterization. However, the deployment of these technologies is not robust as pricing of such equipment prohibits widespread utilization. Consequently, reviews of such equipment, as they relate to their performance in the scrap industry specifically, are primarily advertised through the vendors themselves. Publications aiming to highlight potential opportunities and covering the myriad of limitations that arise when it comes to integrating technology into the scrap process are seldom found (Brooks et al., 2019). Material characterization for yards is especially complex because managing for volume means initiating the identification and sorting process based on a material's physical properties, but secondary operations necessitate materials be grouped by chemical composition.

Certain technologies are able to exploit a metal's distinct physical properties; thus, allowing them to divert and group metals of *similar* size, shape, density, conductivity, and/or reactivity. These technologies can be acknowledged as *integrated technologies* because when they are purchased and used, they become an integral part of the operation's process. **Magnetic separation**, for example, is an industry-wide staple that uses magnetic attraction to extract ferromagnetic metals such as iron, nickel, and cobalt from waste streams, leaving behind nonferrous (NF) metals and non-metallics. There are three main types of magnets: permanent, electromagnetic, and rare-earth (RE) magnets. All have several configuration possibilities, allowing installation to be unique to a yard's design and needs. Prices do vary but overall, they are a low cost, high reward mechanism for separating out large quantities of low-value ferrous metal from the more profitable non-ferrous. The value difference here is noteworthy– for ferrous metals may comprise the majority of the scrap volume, but nonferrous (NF) metals (e.g. aluminum, copper) make up more than 50% of the value for total earnings of the recycling industry (Institute for Scrap Recycling Industries (ISRI), 2020). **Eddy Current conveyers**, equipped with NdFeB magnets, are choice equipment for segregating NF and are often used in conjunction with shredders to manage automotive shredder residue (ASR). Unlike magnetic separation, the eddy current technique works to take advantage of the contrasting conductivities of the mixed NF metals and repels them different distances accordingly (Gaustad et al., 2012). **Dual energy x-ray transmission (DE-XRT) technology** can be applied as a part of a conveyer system. As material passes through the x-ray source, the atomic densities are identified and then distributed into different chambers accordingly. It is capable of distinguishing light (e.g. Al, Mg) from heavy (e.g. Cu, Pb) elements, as well as sorting out non-metallics, but the resolution issues prevent it from being capable of separating by specific alloy (Brooks et al., 2019); although, the latest equipment released by TOMRA claims high resolution capabilities *and* the ability to sort out fractions half the size of previous instrumentation (*TOMRA X-TRACT*; Toto, 2019). DE-XRT is an especially attractive option because it isn't interrupted by surface contamination, a barrier for most characterization techniques. **Prompt gamma neutron activation analysis (PGNAA) crossbelt analyzers** can provide an average elemental composition for the entire feed but cannot be used for individual characterization (Gesing & Wolanski, 2001). For instance, a customer, such as a mill, may offer premium pricing for loads of steel that have an overall copper composition of less than 0.25% (copper is considered a contaminant in steel processing), PGNAA is a technique capable of verifying this. While these technologies have incredible capabilities, cost is a substantial limiting factor and many are still being evaluated as to their efficacy with mixed scrap, thus, utilization is often determined by the yard's volume and feed.

One method with vast capabilities that has come down considerably in costs over the last decade is spectroscopy. There are different types of spectroscopy analysis that can be used to verify the elemental composition, but they are much more commonly seen at the laboratory scale. *Laboratory or Benchtop Technologies* include optical emission spectroscopy (OES), laser induced breakdown spectroscopy (LIBS) and x-ray fluorescence (XRF). All these methods have long been recognized for their abilities to perform Positive Material Identification (PMI) testing, an analysis that determines the chemical composition of a metal/alloy. **Spark OES** in particular, has been trusted by the metallurgical community since the 1940s and is regarded as the most trusted in precision and accuracy still to this day (Bengtson et al., 2017). These sophisticated instruments are capable of high speed analysis and have the ability to analyze elements Lithium through Uranium, including C, N, P, and S, with the aid of argon gas [on solid materials] (Bengtson et al., 2017; "Element Materials Technology," 2021; Günther et al., 1999; *What is Optical Emission Spectroscopy (OES)?*, 2021). **LIBS techniques** have a much longer history of being used for assessments in archeology, geology, and mining but its most recent application for metallurgy offers something promising to users—especially when it comes to aluminum scrap sorting (Bell et al., 2003; Noll et al., 2001; Noll et al., 2014; Noll et al., 2018; Rakovský et al., 2014; ResearchandMarkets.com). The capabilities and appeal for LIBS are wide ranging because the measuring distances (i.e. the distance between the instrument and the object being identified) are adjustable and the devices typically offer rapid read times (Noll et al., 2018). Nonetheless, LIBS is a surface technique, and although it has the ability to make ablations on the surface of material, surface coatings and contamination are still a challenge to accurate reads. Similar to OES, LIBS is capable of detecting the majority of elements in the periodic table— with fluctuating accuracy depending on the material being assessed, the concentration of that element, and the instruments' limits of detection (LOD) (Bengtson et al., 2017; Noll et al., 2018). **X-ray fluorescence (XRF)** varies from OES and LIBS in that rather than creating a plasma from which to measure energy emissions, an x-ray source is utilized to excite and then eject an electron resulting in an inner orbital vacancy; the energy produced when filling this vacancy is what is measured. Another noteworthy difference is that use of x-rays poses additional human health and safety risks in the form of ionizing radiation, thus, proper training and protection need be taken seriously. Although a detailed scientific explanation of x-ray spectrometry is outside the scope of this paper, it is useful to know that XRF instrumentation capabilities fluctuate based on four main components: the excitation source, the specimen presentation system, detection system, and the data collection and signal processing system (Marguí & Grieken, 2013). Modifications to these areas directly impact what elements can be detected, the LODs for particular elements, energy resolution (ability to decipher between fluorescent peaks that may be similar or overlap), detection efficiency (amount of ionizing radiation that is picked up and actively measured), and naturally, costs associated with purchasing and maintaining the instrument (Marguí & Grieken, 2013). The challenge with XRF is that certain tweaks to the design can allow it to outperform other PMI techniques in accuracy but only if the material in question corresponds to the design of the instrument. Now this may seem obvious— an instrument used to detect something it's specifically designed to detect, should be good at it. However, the design and assembly of XRF instruments has often meant choosing between identifying light vs. heavy elements, which has been one of the top complaints by metal recyclers who, as made evident, need PMI technology that can represent both ends of the periodic table.

The global PMI market consists of approximately 20 competitors and the industry is projected to grow to USD $2.89 billion by 2023, up from USD $1.99 billion in 2018 (ResearchandMarkets.com). Although the market is flourishing, it is rare and unlikely for recycling facilities to house *benchtop technologies,* for this type of equipment is pricey and requires delicate care; descriptors that fall on deaf ears in a scrap yard. Even if costs for the equipment and the ability to house it were not a factor, the reality is that yards are intended to function at a very fast pace and that's an aspect that cannot be ignored. Sending out material or setting it aside to be tested causes lag times in productivity, and unless there is a significant tonnage of the material in question, the likelihood of it being comingled over pausing for lab analysis is very high. Furthermore, these methods involve either sample alteration or a level of sample destruction and are not constructed to analyze scrap "as is" (i.e. in its original form) — unless the sample is already a certain size and shape, with a homogenous surface, void of coatings. *Laboratory scale technology* does not fit in naturally with the flow or ruggedness of a scrap yard and that's simply because, it was never designed to. Although these instruments offer the level of identification that the "scrap gap" demands, they aren't practical for large scale improvements.

Handheld analyzers (HHs) have been designed to take the capabilities of the affixed XRF and LIBS benchtop technology and package it into a portable tool that can perform PMI in seconds. A discovery in 1966 revealed that a Li-drifted Si detector could be used in place of the analyzing crystal required for wavelength dispersive XRF (WDXRF) systems. This led to the development of energy dispersive XRF (EDXRF) systems that were simpler and thus, more economical to design, paving the way for the creation of a portable XRF handheld instrument that could be used in-situ (Marguí & Grieken, 2013; Potts & West, 2008). As for LIBS systems, according to Noll, the reduction of laser pulse energies and average radiant fluxes is what allowed for the miniaturization of LIBS instrumentation (Noll et al., 2018). Manufacturers are continuously working on improving analysis speeds for XRF in order to put them on par with the speed of a LIBS handheld analyzer. Analysis for heavy elements have been at a similar pace for some time but it was only as of late, that a few XRF handheld manufacturers were able to provide this for light elements as well. Obtaining information on the applications and capabilities of these instruments is challenging due to the level of ambiguous terminology that is referenced in research studies. Terms like *portable*, *mobile*, and *handheld* are often used interchangeably to describe instrumentation that is easily transportable and can perform on site analysis (a weight range that can vary anywhere from 1-2kg to 15kg). Furthermore, searching for papers that yield results of handhelds, the style used in our study (Figure 3.2), are often assessing the instrumentation primarily to confirm or compare a chemistry to its non-portable version, and/or precision and accuracy needs from the standpoint of a primary or secondary producer. There are no studies to date that evaluate several different XRF and LIBS handhelds by observing how the two technologies perform in comparison with each other, across different instruments of the same technology, and on comingled scraps. Due to there being so many uncontrolled variables when it comes to how and in what form scrap is received, it would be significant to see the results of how handhelds perform on these rugged, coated, contaminated scraps (versus prompt scrap) as to better understand what we can reasonably expect from the instrument and what will be required of the operator.

All manufacturers of handheld analyzers (LIBS and XRF) have several models and each design focuses on improving safety features, light-weighting, battery life, ergonomics, strength and durability, precision and accuracy, and ease of operation. Inopportunely, as inferred above most of what we know about how these analyzers perform in-field is limited to the manufacturers' claims—claims primarily based on lab testing of cleaned, polished samples or prompt scrap. This is not conducive to understanding their performance under the arduous conditions of a yard and the challenges faced by inspectors when it comes to identification during the inbound inspection process. Short of seeking out scrap facilities that have purchased these instruments and compiling feedback, there is very little work in the space of analyzing a wide variety of obsolete scrap. Therefore, research is needed not necessarily to determine accuracy and precision, because manufacturers already give you this baseline expectation for their instrument(s) (on new production materials), but rather to see how useful they can be in a scrap yard setting. This work aims to determine if HHs can contribute to improved, in-field inspection (over visual) by testing both XRF and LIBS performance on actual scrap samples, maintaining their shape and appearance as found in yards. Analysis will focus on four key challenges faced by yards: 1) how well can the instruments characterize aluminum alloys (wrought obsolete, wrought prompt, and cast) 2) what precision and accuracy exists for identifying obsolete ferrous scrap 3) are there significant variations between XRF and LIBS for other common nonferrous scrap (red metals, stainless, tungsten, molybdenum, titanium, and lead) and 4) what performance should we expect when assessing coated vs. bare scrap? This evaluation will help us better understand what level of identification metal recyclers are capable of achieving with the assistance of this technology.

3.3 Methodology

Sample selection and collection

The scrap selection for our experiment was controlled and determined by three main factors: (1) metals that would challenge the reported strengths and limitations of the handhelds being marketed, (2) a sample group that would reflect the magnitude of the range of materials that enter scrap yards, and (3) materials that have proven especially challenging and are often identified incorrectly during visual inspection. We shared these considerations with a number of scrap yards when we initiated the scrap collection process and received samples with a variety of finishes: coated/plated, oily, polished, painted, crinkled, coarse, and smooth. Our request also led to obtaining samples that ranged from simple (primarily one major element e.g. copper tubing) to complex chemical compositions (multiple major and minor elements e.g. stainless steel and aluminum alloys) as well as a representation of the various metal groups: from heavy (Pb, Cu, Fe) to light (Cr, Zn, Ti, Al) and a couple refractory metals (Mo, W). Additionally, within the samples collected we were able to evaluate the impact of substantial fluctuations in size, from thin to thick, along with borings and turnings to plates more than a foot long. Images of the samples evaluated in this study can be found throughout the results section.

Sample preparation

In seeking to identify how XRF and LIBS handheld analyzers perform when used on the spot during in-field visual inspection, it was important that we do as little modification to our samples as possible. However, because we were also looking to observe degrees of accuracy from the units, we had to consider known limitations of the technology. LIBS being a surface technique and XRF having a defined, set beam penetration depth, surface coatings are areas where both instruments are inherently limited. Technically, the instruments are correctly identifying what they are reading, but they are often unable to measure the entire chemistry of the metal. To account for this, a Dremel tool was used on a section of several samples to grind and polish beyond the coatings (Figure 3.1). This is still a comparable evaluation between the instruments' abilities and how visual inspection is performed– for a trained inspector will often be equipped with a file to check for and remove surface coatings.

Additional sample preparation consisted of giving all samples an identification code and marking each of the samples in three locations where the readings would be administered (Figure 3.1). This would allow us to observe if, or the degree to which, the readings would fluctuate on the same spot and across the sample. Three readings were taken on each designated location for a total of nine readings per sample.

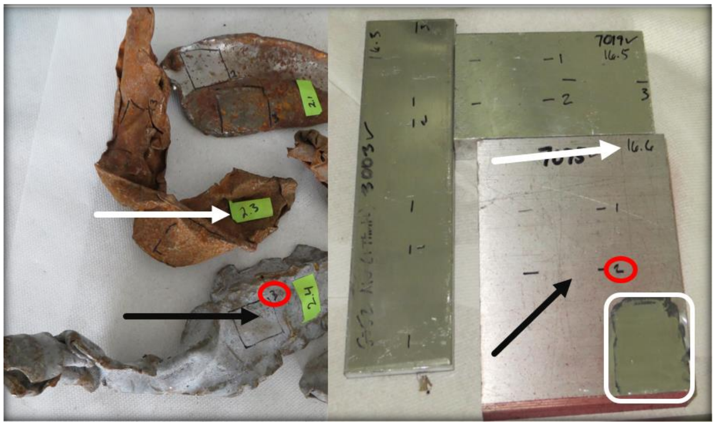


Figure 3.1 Visual of how samples were prepared. White arrows point to the sample's identification code, that were later assigned descriptor IDs for reporting results (See Figure 3.4, 3.5, 3.8, 3.12, 3.14, 3.16, 3.17). Black arrows show where readings were administered, and the red circle identifies on which of the 3 spots the reading is being taken. In the bottom right corner is an example of a sample that needed to be buffed due to possible interference of the surface coating (area within the white box).

<u>XRF and LIBS HH-analyzers</u>

A total of 6 HH-analyzers were used to evaluate performance; three different models of XRF (XRF1, XRF2, XRF3) and three separate LIBS units (LIBS1, LIBS2, LIBS3). Performance was averaged across the instruments to represent the abilities of the technology itself (XRF vs. LIBS). In order to obtain the individual units, we reached out to manufacturers with loaner programs and scrap facilities that would allow us to borrow their equipment. The handhelds we received are listed below (Figure 3.2).

	Manufacturer	Model	
XRF	Olympus	XR03-InnovX Delta Alloy	
	Thermofisher Scientific	Niton XL3T	
	Olympus	Vanta C Series	
LIBS	SciAps	Z - 200	
	Rigaku	KT- 100 Katana	
	TSI	Chemlite	

Figure 3.2 Handhelds evaluated in this study.

All manufacturers provided training for their instruments along with a representative who was knowledgeable and helpful for troubleshooting and answering any questions; this level of customer service comes standard with the purchase [or loan] of an analyzer. Each instrument has copious capabilities [beyond pressing the trigger] and a unique interface; it is in this area where instruments distinguish themselves from one another most and why training is essential.

The handhelds in this study were set to “Alloy” mode upon analysis (TSI’s comparable mode is known as “Assay” mode) and calibrated before each use; it is critical that your analyzer is set in the correct mode when taking measurements or you can end up with skewed results (i.e. if we were looking at precious metals specifically, we would need to change modes). Although the analysis modes across instruments were kept consistent, the default and variation settings for the LIBS handhelds’ “cleaning” mode would fluctuate slightly from instrument to instrument. The function of the cleaning mode is to “fire” several “shots” prior to a reading as a form of sample prep for eliminating surface contamination. This is an aspect of the instrument where experience and training will serve useful– for the operator has the ability to adjust this as they see fit. However, modifications such as these will add several seconds to the total analysis time, removing one of the LIBS’ most distinguishing features and putting it on par with the read times expected of an XRF instrument. Lastly, both XRF and LIBS instrumentation required that the detector be completely flush with the surface of the sample, even the most minor gaps could prevent the analyzer from taking a reading (see Figure 3.3). In such instances, reading placement had to be altered from the designated area but careful consideration went into making certain such modifications were only minor.

Figure 3.3 Small gaps between the surface of the detector and the sample, such as the ones circled in white above, prevented the instrument from taking readings.

Spark-OES

Spark-OES is the most commonly used form of PMI testing for the metals industry. Spark-OES is a semi-destructive, benchtop technology that can perform measurements on scrap that has a flat surface, free of coatings. Typically, scrap that is not of this nature (obsolete) is melted down to create what are often referred to as “buttons.” These buttons are solid, with a flat, coat-free surface– they maintain the chemistry in question but as a modified form of the scrap. Subsequently, we were unable to collect OES readings [for comparison] on the majority of our obsolete scrap samples as we did not want to modify samples by melting them, and therefore prompt is the focus for accuracy comparisons.

We used an Ametek SpectroMaxx for our spark-OES analysis. The instrument has two key components for its operation, a water line that feeds through it and Argon gas. Similar to XRF and LIBS it is a fairly quick analysis, approximately 34 seconds from start to finish. Runs must be organized according to base metal because a different standard, as well as a thorough cleaning of the probe and additional components, is required between the aluminum-base, copper-base, and iron-base (includes stainless) samples. In order to prevent cross-contamination, Kimwipes and an aluminum wire brush were used for cleaning when calibrating for a new standard, and to prepare the instrument between samples of the same base metal and after each reposition. Further maintenance for the Ametek includes an “iCAL standardization” that is required once a month and takes approximately 2 hours.

Data Analysis

We calculated the average, standard deviation, and coefficient of variation (COV) of the major and minor elements for each sample. The decision to use COV to look at repeatability over merely evaluating with standard deviations was due to having several cases where although the goal was to retrieve 9-12 data points, we could only measure 3, or were able to take upwards of 15-20. Using $COV = \frac{\sigma}{\mu} \times 100\%$ allowed for further interpretation of the data because we could now make comparisons between samples where the total number of data points collected from each handheld varied. A high COV indicated significant fluctuations between readings across a sample or even upon the same exact spot a previous reading was taken. Whereas low COVs, especially those closest to 0%, demonstrated high reproducibility capabilities of the instrument(s). This metric was also helpful for evaluating and comparing results between base and trace elements within samples as well as across sample groups. As a result, we were able to compare the differences and similarities between XRF and LIBS for samples across different metal groups, and between alloys within the same metal grouping; for a subset of samples, we were able to compare XRF, LIBS, and OES-Spark.

3.4 Results and Discussion

Ferrous scrap

Iron and Steel

Ferrous scrap is significantly less in value (per ton) than most non-ferrous scrap but in terms of volume, it is the most recycled material globally. While most frequently understood as iron or steel, there are several different ways to group ferrous scrap which can lead to premium pricing (as some segregation can result in a better melt for the mill). Figure 3.4 displays the samples used for this study; visually it is clear the extent to which ferrous scrap can fluctuate in appearance. Table 3.1 looks at the outcome of measuring the Fe percent by weight composition in the ferrous scrap and in it you can see that both XRF and LIBS proved to have negligible differences for variables such as repeatability and compositional averages. Although margins were small, a closer look did reveal that the calculated COV values for XRF were lower for 13/16 samples. On eleven of the samples we were able to compare the XRF and LIBS measurements to OES (see Table 3.1). We observed that 82% of the sampling showed LIBS and OES values varied by a larger margin than the XRF and OES values. The largest difference in percent composition between XRF and LIBS for Fe is found on sample FS3, a sample that has high rust contamination, but the smallest difference is found on sample FS2 also high in rust contamination. The greatest difference between XRF/OES and LIBS/OES for percent composition of Fe are both found on D-2 tool steel (sample FS14). The smallest difference in reading fluctuations (COV) between the XRF and LIBS is on sample FS4, a low alloy carbon steel. The largest COV delta appeared on sample FS5- this was mostly due to **one** of the LIBS instruments struggling to surpass the top layer of the material which indicated to the instrument high chrome content and identified it as stainless alloy as opposed to a carbon steel. FS5 will not be discussed in the surface coatings section because only one out of the six instruments displayed value differentiations which leans seemingly more toward an instrumentation limitation and not a technological one. To see the outcome for other scrap samples of Figure 3.4, refer to Table 3.1. The averages for the percent by weight composition of Fe in the ferrous scrap is calculated across all instrumentation (XRF, LIBS, and OES), COV values are also reported to accentuate the instrument's reproducibility (COV of OES is not included because all the returned measurements were the same and therefore the COVs were all equal to zero).

Figure 3.4. Ferrous scrap includes a variety of iron (Fe), carbide steel, tool steel, rebar, and plate and structural. Above is the assortment of ferrous scrap reviewed for this study with the sample ID numbers referenced below each image. Descriptors below the ID number are based off the condition of image and demonstrate the variety of ways the metal could be sorted. Superscripts indicate the following: original product[1]; how it will be proccessed[2] (or how it was processed prior to our collection of the sample); likely commodity grouped with[3]. Superscripts "2" and "3" depend on volume and equipment; if a "2" is not present, that means no processing required.

Average Fe% & % Difference							COV %		
Sample ID	XRF	LIBS	OES	XRF LIBS %Δ	XRF OES %Δ	LIBS OES %Δ	XRF	LIBS	XRF LIBS Δ
FS1	97.6	98.6	-	1.05	-	-	1.03	1.38	0.35
FS2	96.2	96.3	-	0.19	-	-	2.10	3.07	0.97
FS3	93.5	97.2	-	3.85	-	-	3.96	4.37	0.41
FS4	98.1	98.5	98.3	0.37	0.20	0.16	0.47	0.45	0.02
FS5	99.5	96.2	99.6	3.33	0.05	3.38	0.37	5.64	5.27
FS6	97.0	97.4	96.8	0.44	0.15	0.60	0.23	0.54	0.31
FS7	96.8	97.4	97.1	0.67	0.30	0.37	0.70	0.84	0.14
FS8	91.3	93.2	91.7	2.04	0.38	1.66	0.92	0.73	0.19
FS9	95.2	96.2	95.8	1.09	0.64	0.45	1.97	0.61	1.36
FS10	97.0	96.3	97.6	0.80	0.60	1.39	0.61	2.61	2.00
FS11	97.4	97.8	97.6	0.38	0.16	0.22	0.26	0.63	0.37
FS12	84.2	85.4	83.8	1.43	0.43	1.86	1.84	2.68	0.84
FS13	83.9	85.5	82.6	1.82	1.66	3.48	1.55	4.77	3.22
FS14	84.9	87.1	80.8	2.58	5.01	7.59	5.91	8.53	2.62
FS15	96.2	95.3	-	1.02	-	-	2.39	3.08	0.69
FS16	95.9	93.6	-	2.40	-	-	1.26	3.56	2.30

Highest Value
Lowest Value

Table 3.1. Data representing averages and repeatability across all instrumentation to show the similarities between XRF and LIBS in the evaluation of the Fe percent composition by weight in ferrous scrap. Samples FS4 – FS14 show how XRF and LIBS compare to the results obtained from OES analysis. COV for OES measurements was equal to zero thus, the difference between OES/LIBS and OES/XRF is just the COV value itself. Samples with the most notable differences are highlighted based on the key to the upper right. Percent Difference = $\frac{|A-B|}{(A+B)\div 2} \times 100$

<u>Obsolete and Prompt Aluminum Scrap: Wrought and Cast Alloys</u>

Base Metal Analysis

When it comes to LIBS and XRF technology, one of the prevailing beliefs is that LIBS out-performs XRF for aluminum alloy identification. However, our base metal analysis of 14 wrought samples (Figure 3.5) showed XRF and LIBS having similar identification results. When averaging the coefficient of variation (COV) for aluminum across all the wrought samples, we saw no statistically significant difference between XRF and LIBS for obsolete (XRF, LIBS COVΔ=1.42%) nor prompt (XRF, LIBS COVΔ=0.40%). Based on COV calculations, XRF and LIBS instrumentation demonstrated very high reproducibility across all wrought prompt aluminum (WPA) samples, never exceeding a COV of 1.6%. For wrought obsolete aluminum scrap (WOA), XRF and LIBS both had 3 samples with COVs > 9%, where the rest of the samples only differ from 0.01% to 4.07%, with neither instrument average proving to lead on lower or higher COVs.

Figure 3.6 shows examples of the results found on WOA scrap; the figure highlights the range and similarity of the readings produced by both XRF and LIBS HH analyzers. The graphs in Figure 3.6, demonstrate the extreme [and lack of] differences in the averages and precision (COV) that can be seen between the two types of instrumentation on WOA scrap. The scrap samples used in Figure 3.6 demonstrate the inconsistencies that result from surface contamination and surface irregularity, two things that are difficult to avoid when dealing with obsolete scrap. WOA10 is an example of obsolete aluminum scrap that consists of a flat, homogenous surface with little to no contamination and it is in this instance, that both instruments display a significantly lower variation and higher confidence in their measurements.

For four WPA samples we were able to look at the accuracy by comparing them to a spark-OES analysis (Figure 3.7). Three out of the four showed XRF being closest to the Al% by weight average value of the OES results, and those three also displayed less fluctuations between readings than the LIBS results; indicating that for these selected samples, XRF had better precision and accuracy (for aluminum). Figure 3.7 also gives some insight into how these technologies compare with OES-Spark laboratory instrumentation on wrought prompt samples and further demonstrates that the instrumentation's performance, whether it be XRF or LIBS, improves drastically when there is not a clear means of interruption between the sample and the instrument (i.e. surface contamination and irregular surfaces). Precision and accuracy differences on the WPA could be considered negligible when zoomed out, but a closer look reveals differences of up to a full percent in the average % composition and shows how much "noise" XRF and LIBS actually exhibit when compared to spark-OES. What seem like minor or maybe even insignificant variances in percent composition, such as a single percent or less, can in fact be extremely important when trying to make high purity products. These small percentage differences for large batches can have a large influence on the volumes of additional materials needed for dilution. Furthermore, XRF and LIBS both display lower averages of aluminum (% composition by weight) meaning that there is always going to be some degree of interference in using surface technology for identification. The basis for this assertion can be seen more clearly in the following section on alloying elements (Figure 3.11); both XRF and LIBS display higher combined Fe and Si levels in every case when compared with spark-OES.

Cast aluminum (CA) sample images and descriptions can be found in Figure 3.8. The readings returned from the cast samples proved to be very similar to the wrought results with four out of the seven samples showing XRF having the lower COV percent on average; although, two of the largest individual COV values were seen from the XRF instrumentation displaying a couple values > 20% (Figure 3.9: A. & B.). All other cast samples showed negligible differences in COV values, but the majority of the samples did have XRF leading in reproducibility (lower COV values). However, all Al % composition by weight averages were consistently of lower value using the XRF instrumentation, never exceeding 85% Al but dropping as low as 65%; the reason for this becomes clear when reviewing the results depicted in Figure 3.11, showing extremely high percentages of Fe and Si in comparison with the LIBS. LIBS Al% composition by weight ranged from 76%-90%. Repeatability proved overall to be more difficult on the cast samples than the wrought for both technologies and across all instruments.

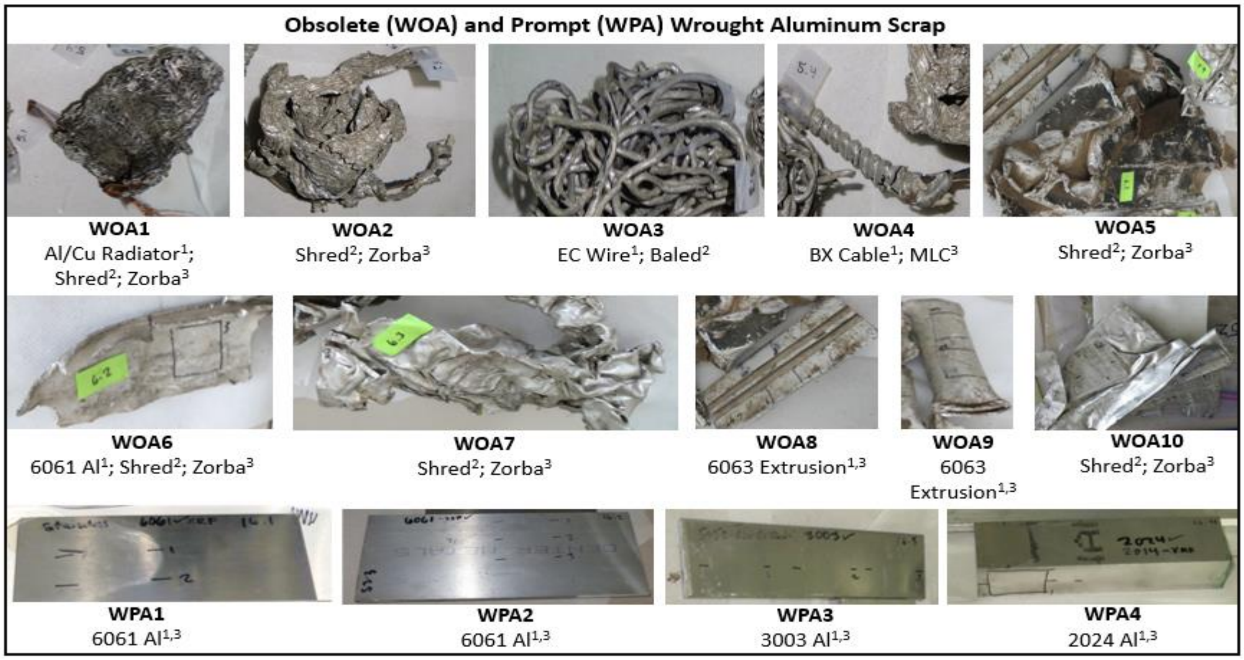


Figure 3.5 Above are the wrought obsolete (WOA: first two rows) and prompt (WPA: third row) scrap samples evaluated in this section; sample IDs are referenced below each image. Descriptors below the ID number are based off the condition of image and demonstrate the variety of ways the metal could be sorted. Superscripts indicate the following: original product[1]; how it will be proccessed[2] (or how it was processed prior to our collection of the sample); likely commodity grouped with[3]. Superscripts "2" and "3" depend on volume and equipment; if a "2" is not present, that means no processing required.

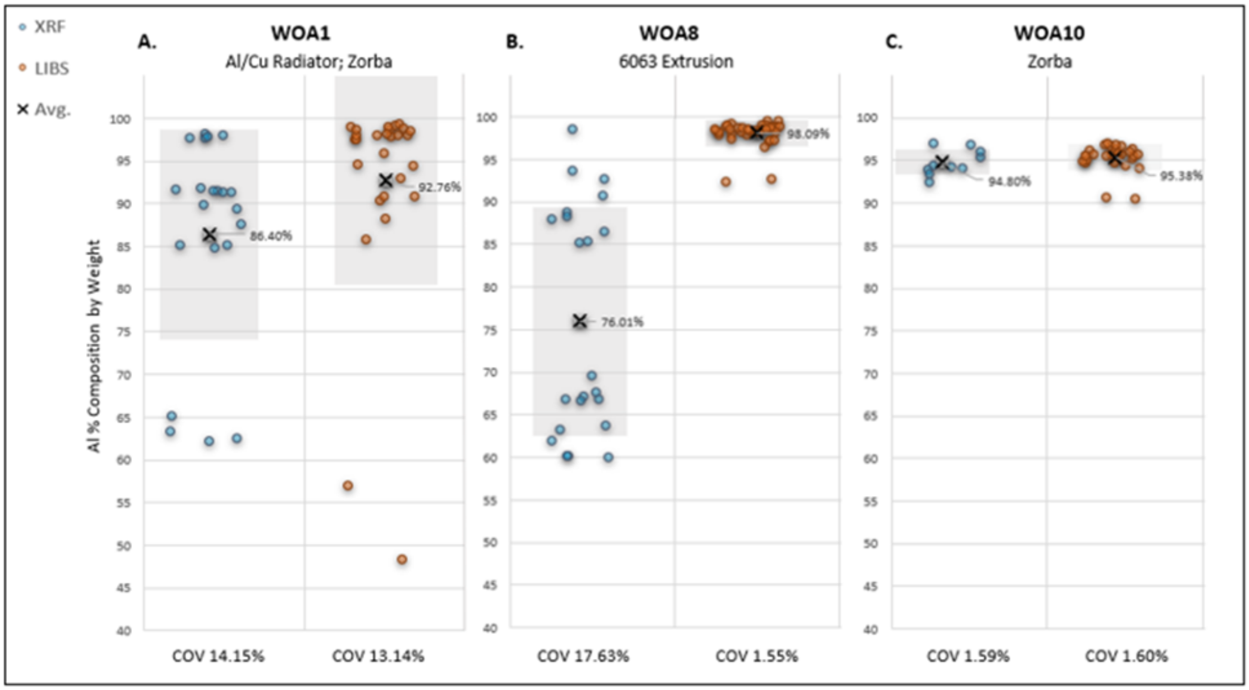


Figure 3.6 Aluminum percent composition readings taken from the wrought obsolete aluminum (WOA) samples; grey boxes indicate standard deviation, the "x" highlights where the average of the data sits, and COV calculated for the data is indicated below the graph. These results highlight the range and similarity of reproducible readings by both XRF and LIBS HH analyzers. Sample WOA1 demonstrates how extremely nonhomogeneous surfaces and products with compounded metals (Al/Cu radiators have an aluminum shell with copper tubing running through) cause a lot of noise and uncertainty in reading results. WOA8 is a 6063-extrusion but one that most likely came out of a shred pile and thus, proves to be more problematic for the XRF instrument than the LIBS due to the LIBS' "cleaning shots" function. WOA10, although appearing as if it has gone through a shredder (refer to images in Figure 3.5), has maintained a surface with a smooth, relatively clean exterior, allowing very high and similar reproducibility for both instruments.

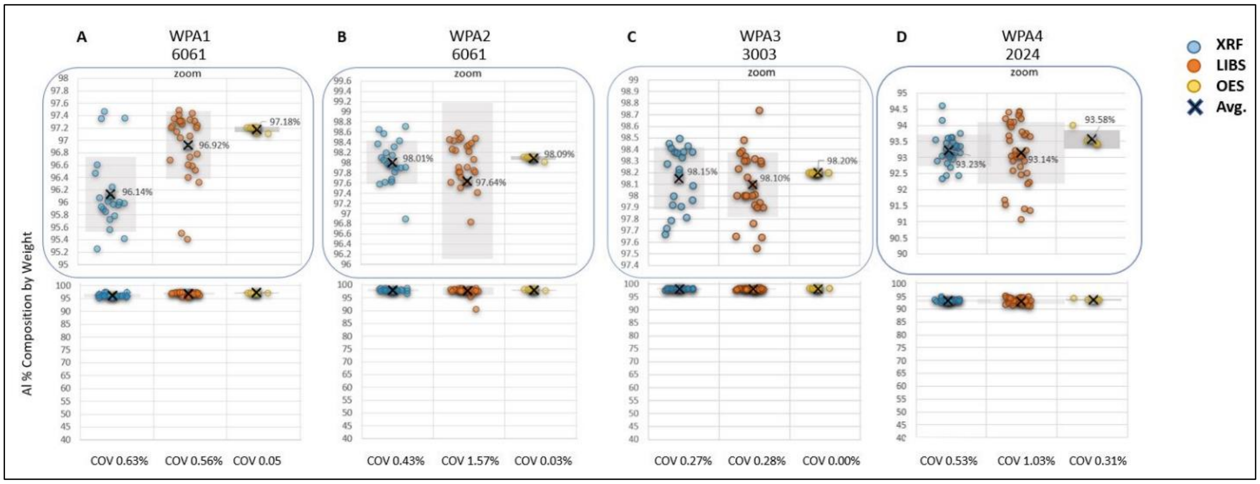


Figure 3.7 Due to the superior condition of the wrought prompt (WPA) samples, we were able to compare performances between XRF, LIBS, and OES-Spark. Sample WPA1, a 6061-aluminum alloy, is the only prompt sample that the LIBS outperformed XRF. WPA2, also a 6061-aluminum alloy and WPA4, a 2024-aluminum alloy shows XRF outperforming LIBS by a slightly greater magnitude for both precision and accuracy. Sample WPA3 is a 3003-aluminum alloy, the results from this sample exhibit the most minimal difference between all instruments.

Figure 3.8 Above are the cast aluminum scrap (CA) samples assessed in this section; the sample ID is provided below each image. Descriptors below the ID number are based off the condition of image and demonstrate the variety of ways the metal could be sorted; the superscripts are applied the same as they are in *Figure 3.5* for the wrought aluminum samples.

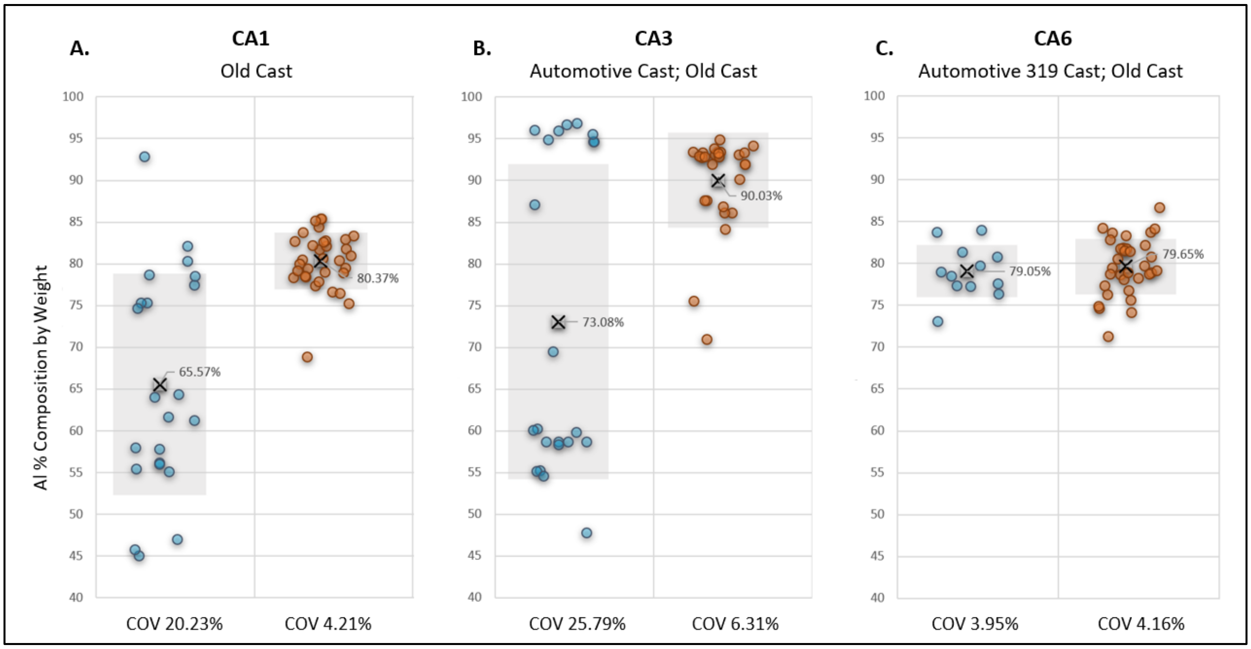


Figure 3.9 Cast aluminum samples that stood out the most in our results are displayed above. Sample CA1 and CA3 above indicate samples where XRF struggled the most, distributing the highest COVs out of all the aluminum samples (including wrought) at COVs> 20%. Sample CA6 presents the most similar results between XRF and LIBS in terms of COV, Al% by weight, and standard deviation. All other cast samples showed negligible differences in COV values, most XRF holding lower COV percentages. All Al % by weight composition averages were consistently higher using the LIBS instrumentation.

Alloying Elements

Many of the contained elements (i.e. alloying elements) in aluminum (e.g. Fe and Si) are crucial for achieving desired performance properties (Wagstaff, 2018). However, many of these alloying elements can also develop into tramp elements or impurities as they accumulate in the recycling process; this leads to ranges that exceed the designated maximums for compositional windows. There are a variety of processes that take place before a secondary processor, such as an ingot or billet maker, receives material. Different methods of collection, shipping and/or utilizing methods such as shredding and torching, are all necessary steps for pre-processing and handling materials. However, with every additional step, the likelihood of contamination increases, and this directly translates to the accrual of unwanted elements. This is a major concern for secondary processors as it highly influences batch planning and will continually impact the production of future goods. XRF measured higher levels of Si across all aluminum types, and XRF also measured higher Fe levels on 16 out of 23 samples (See Figure 3.10) but all prompt samples have the LIBS measuring higher Fe levels (Figure 3.10 & 3.11). OES and XRF measured similar compositions for Fe while LIBS and OES have similar results for Si (Figure 3.11).

In the previous section, we discussed how there were two cast samples, CA1 and CA3, that demonstrated large fluctuations, equating to COVs of greater than 20% (Figure 3.9). If you then observe them in Figure 3.10, you'll notice how the XRF results noticeably protrude beyond all others revealing extremely high and distinguishingly different Si values than the LIBS results. High COVs in combination with high Si levels is an indicator that surface coatings or contamination are impacting the results; different surface coatings and the contaminants that result from them can be found in Table 3.5.

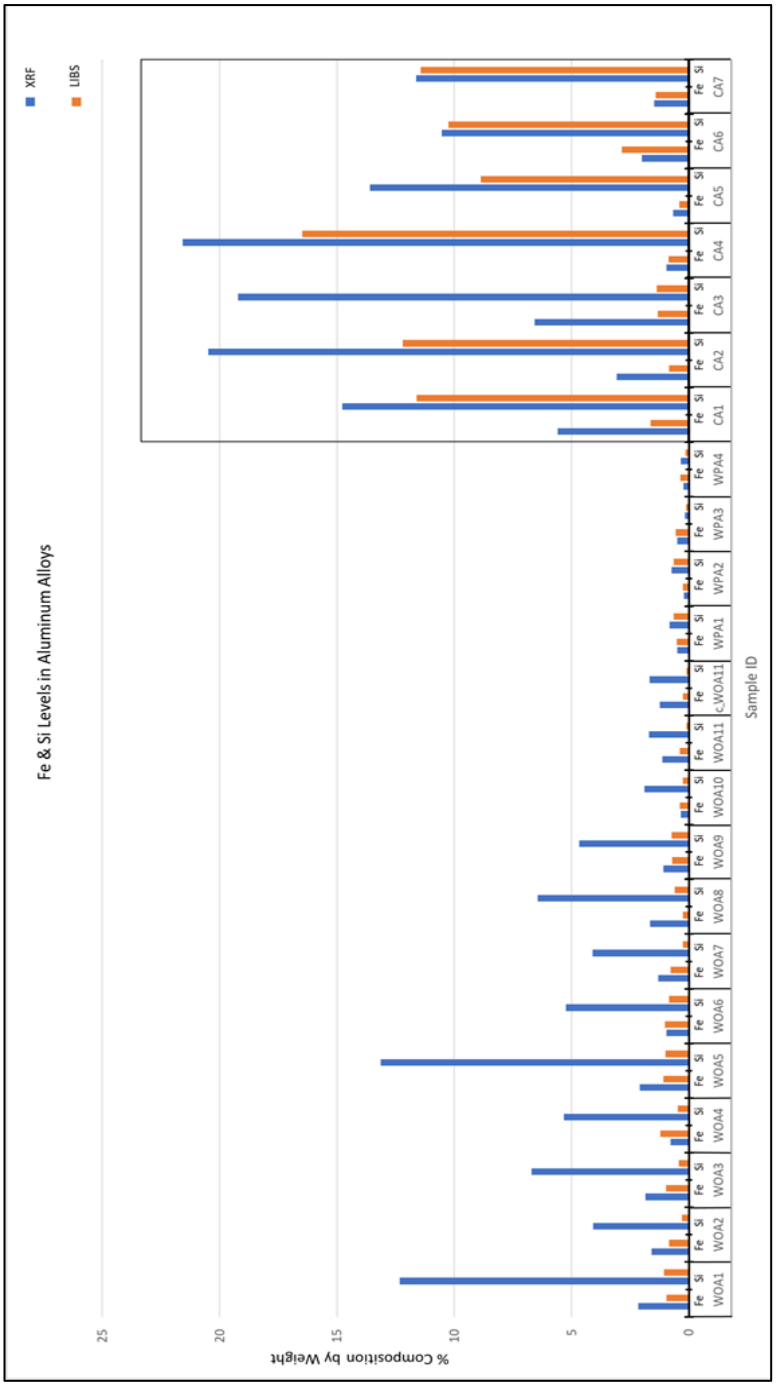


Figure 3.10 The graph above shows the levels of Fe and Si in all the aluminum samples pictured and discussed in *alloying elements* section (WOA11 & c_WOA11 are additional aluminum samples included in the graph but not pictured in this section because a detailed analysis is better suited for the *surface coatings* section below). The boxed samples indicate aluminum cast samples, the rest are wrought aluminum.

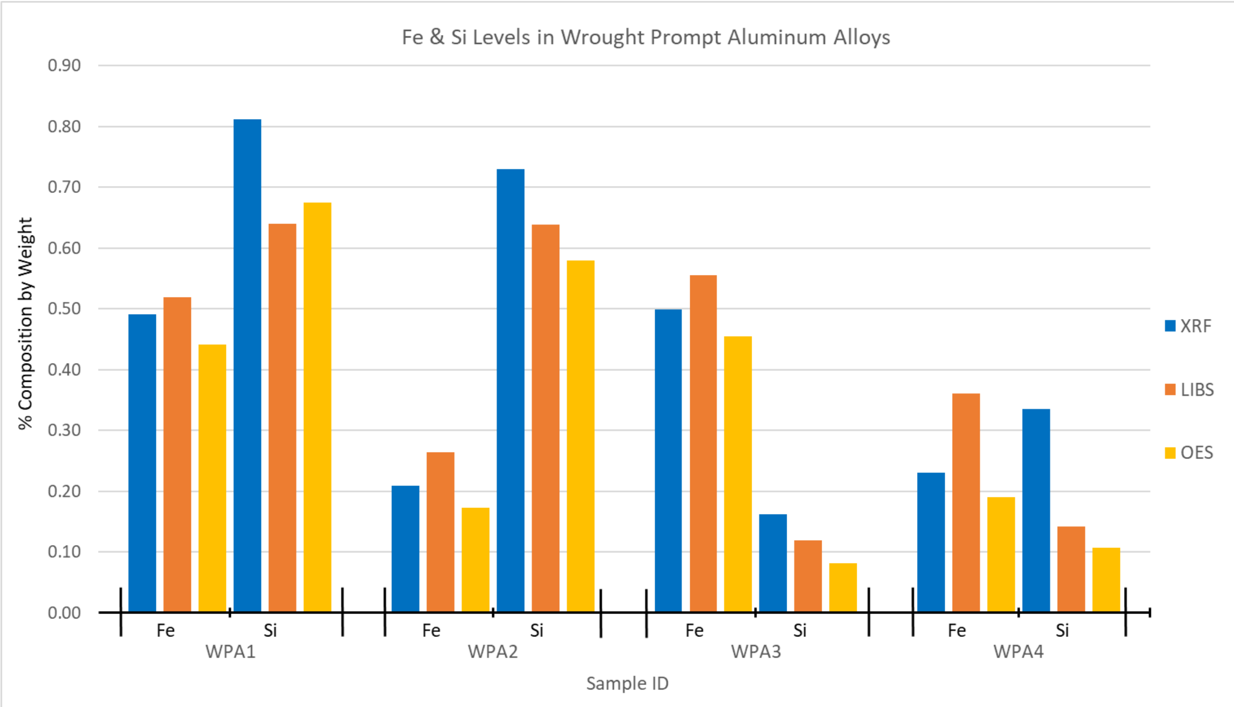


Figure 3.11 This graph is a zoomed in view of Figure 3.10 but highlighting the results of the prompt aluminum samples and then further comparing them to the results obtained from OES-Spark Analysis.

Specific Alloy Identification (Grade Matching)

Each instrument performs what is referred to as "grade matching." Table 3.2 displays all the varieties of grade matching that were produced from the readings. "NM" refers to "No Match," meaning the instrument either could not identify the alloy based off the composition or the instrument grade library didn't include that specific alloy. Alloys in bold indicate that both the LIBS and XRF instruments identified that alloy during the analysis. Additionally, only **the top ranked** match results are referenced in the table (some instruments had up to 3 "best matches"). Furthermore, the table does not quantify the number of times the grade match appeared (or didn't), the purpose of the chart is to show that across all instrumentation and also within the same handheld, it is rare for the measurements to only identify with one alloy specification. The only exception to this was on Sample WPA3 – the prompt 3003 aluminum alloy. The other aspect this table highlights is how the fluctuating silicon levels (seen in Figure 3.10) (most likely from surface contamination), confuse XRF into identifying a wrought aluminum as a cast; this happened for every one of the obsolete samples in our study.

The results of Table 3.2 bring into question not only whether or not specific alloy identification is always possible but whether it is always necessary. We know that certain amounts or levels of a given element are what dictate batch recipes and directs the amount of dilution required. Therefore, being able to identify those particular compositional percentages may be more important than the instrument's ability to match it to a named alloy in some cases. Furthermore, the reality is that today many alloys have different alloy identification numbers even for the slightest variation in the chemical composition. In other words, if you were to look up the chemistry of a 6061 aluminum in the International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys, you would find 2 types: 6061 and 6061A. Over time, there have been a growing number of modifications to these chemistries due to different tempers being used for rod, bar, tube etc. in different industries. In sum, although the two distinctions are supposed to be a way to determine one or the other (i.e. a specific alloy is associated with a specific chemistry and vice versa), there is a difference between knowing the chemistry of an alloy and having it assigned a specific name. The ability to grade match and the ability to produce the compositional percentages are both of value to the user. The instrument's capabilities combined with an educated operator help to provide a system of checks and balances.

There are also complications that derive from the processing of materials. Yards can't always control the form of which they receive material and that means often having to utilize a simpler, less expensive option that prioritizes profits when "cleaning up" material becomes too costly. In other words, they aren't going to risk losing money allocating time and resources to sort every little piece; this combined with uncertainties in identification causes a lot of material to either be shredded, downcycled, and/or end up in comingled packages. These package designations always start with inbound inspection, which is why reliable technology at this step is crucial and has the potential to maximize the economic and environmental benefits we can gain from the recycling industry, many that are yet to be realized. Inbound inspection is the optimal time to intercept and sort the material; the more you allow material to get moved around, the more likely you will have to overcome possible exposure to contamination due to things such as shredding torching, and comingling thus increasing complications with identification and sorting. Bottom line, all these different measures for handling material that takes place after the instructions issued during inbound inspection are going to make it especially hard for an instrument, no matter it's calibration or grade library capacity, to grade match the chemistries because the alloy is no longer representing its original form.

	Sample ID	XRF	LIBS
Wrought Obsolete Aluminum	WOA1	NM, 356Cast, 360Cast	NM, 1100, 1XXX, 6063, 7072, 7031
	WOA2	NM, 355Cast, 443Cast	NM, 3003, 3105, 7031
	WOA3	NM, 356Cast, 380Cast, 383Cast, 384Cast, 1000, 4043, 4343, 6061	NM, 1100, 7031, 7072
	WOA4	NM, 358Cast, 384Cast, 413Cast, 1000, 4043, 5005, 6005, 6063	NM, 5052, 6040, 7031
	WOA5	NM, 356Cast, 408Cast, 1000, 1100	NM, 3005, 3105, 6005, 6022, 6063, 6111, 6253, 7031
	WOA6	NM, 355Cast, 356Cast, 408Cast, 1000, 1100, 4043, **5005, 6063**	NM, **5005,** 6005, 6022, **6063,** 6253, 7031
	WOA7	NM, 355Cast, 443Cast, 3004,4043, 6070	NM, 3003, 3105, 6061
	WOA8	NM, 356Cast, 1100, 4032, **5005,** 6005, **6063**	3002, **5005**, 6022, 6061, **6063,** 6253, 7031
	WOA9	NM, 355Cast, 356Cast, 4043, 5005, **6063**	NM, 1100, 6005, 6022, **6063,** 6253, 7031
	WOA10	355Cast, 356Cast, **5086,** 6005, 6061, 6063, 6082	NM, 5042, 5052, 5083, **5086,** 5154, 5754, 6253
Wrought Prompt Aluminum	WPA1	6020, **6061**	NM, **6061**
	WPA2	6008, **6061**	5050, 6253, **6061,** 6063
	WPA3	**3003**	**3003**
	WPA4	NM, **2014, 2024**	2007, **2014, 2024**
Cast Aluminum	CA1	NM, 381Cast, **384Cast,** 4043	NM, 380Cast, 383Cast, **384Cast**
	CA2	NM, **413Cast**	NM, 356Cast, 357Cast, 358Cast, **413Cast,** 4343
	CA3	NM, 443Cast	NM, 514Cast, 5082, 5083, 5086, 6082, 7031
	CA4	NM, **390Cast**	NM, 380Cast, 383Cast, **390Cast**
	CA5	NM, **356Cast**, 359Cast, 369Cast, 384Cast, 1000, 4004	NM, **356Cast,** 357Cast, 358Cast, 413Cast
	CA6	NM, **380Cast,** 381Cast, **384Cast**	NM, **380Cast,** 383Cast, **384Cast**
	CA7	NM, 381Cast, **383Cast,** 384Cast	NM, 380Cast, **383Cast**

Table 3.2 "Grade matching" results for all aluminum samples pictured in this section. "NM" refers to "No Match," bolded alloy names indicate that both LIBS and XRF identified that alloy during the analysis. The table only includes the #1 ranked result (instrumentation could have up to three).

"Red metal" scrap

Copper, Red and Yellow Brass

Copper and brass have significantly higher prices than that of ferrous and many other non-ferrous metals (typically 3 times the value of aluminum). Dense metals of high value can be an especially unique area where yards can increase profits, particularly when being able to distinguish brasses and coppers from one another. The XRF instrumentation used in this study demonstrated better reproducibility for two-thirds of the red metal samples (Figures 3.12 & 3.13). In every case except for one, the LIBS instrumentation displayed Cu % composition by weight that the XRF HHs (Figure 3.13). The LIBS displaying much higher returned readings for Cu (% composition by weight) reveals the complications of identifying heavy metals with the LIBS instrumentation. We see a continuation of this struggle when we more closely assessed the Zn results from the brass alloys in Table 3.3. All but one of the Zn (% composition by weight) averages were lower with the LIBS than the XRF findings. However, the one time the value from the LIBS for Zn was comparable to XRF, was also the highest COV for LIBS. Overall, LIBS consistently had much higher COVs for Zn; differences between XRF and LIBS ranged from 8.9 % <COV< 30% (Table 3.3).

Copper content is what buyers are often after (as well as low Fe and Pb); brasses are designated according to the amount of Cu, Zn, and often Pb (sometime Sn) they contain. Yellow brasses range from

~58%-75% Cu, red brasses from ~75%-84% Cu, and variations of strictly copper scrap range from a minimum of ~88% but more commonly 98% and above. The averages calculated for Figure 3.13 indicate that both XRF and LIBS seem able to successfully identify Cu compositions but, although they are seemingly close in value, it is not likely in an in-situ setting to take as many readings as we did for our study. Thus, the larger fluctuations demonstrated by the LIBS instrumentation (higher COV values), indicates that for separation of red metals, XRF may be the superior technology.

Figure 3.12 Red metals include copper, brass (red and yellow), and bronze. The red metal scrap evaluated in this study can be found above with sample ID numbers indicated below each image. Sample ID numbers are accompanied by descriptors below (based off the condition of the image) and demonstrate the variety of ways the metal could be sorted. Superscripts indicate the following: original product[1]; how it will be proccessed[2] (or how it was processed prior to our collection of the sample); likely commodity grouped with[3]. Superscripts "2" and "3" depend on volume and equipment; if a "2" is not present, that means no processing required.

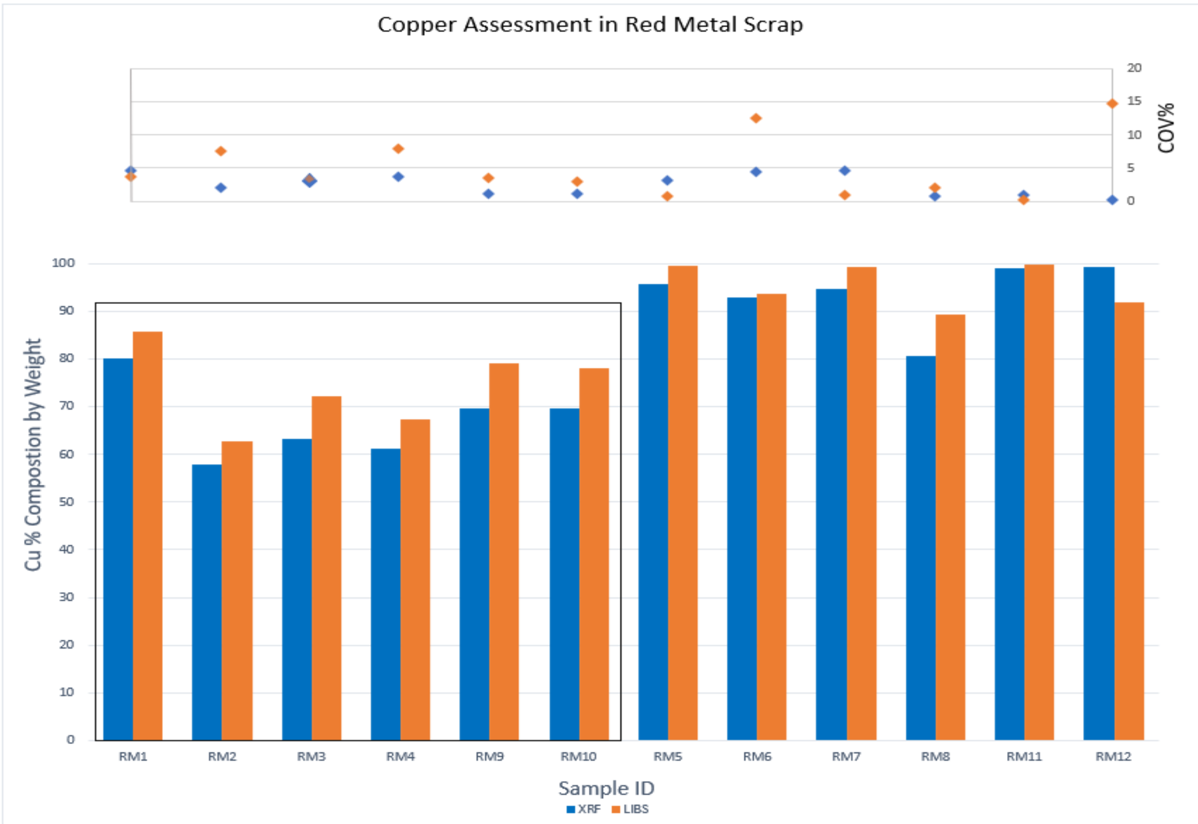


Figure 3.13 Copper analysis for red metals: samples RM1-RM4, RM9, and RM10 are brass (includes yellow and red brass), & RM5-RM8, RM11, and RM12 are copper. Comparison of results between XRF and LIBS copper averages are displayed by the bar graph. The points plotted above the graph shows a comparison of COV % fluctuations for each sample.

Zn						
Sample ID	Avg %			COV %		
	XRF	LIBS	Δ	XRF	LIBS	Δ
RM1	4.6	4.7	0.1	5.7	36.2	30.4
RM2	36.0	34.0	2.0	3.2	13.5	10.3
RM3	33.5	26.1	7.4	3.6	15.0	11.4
RM4	35.8	32.0	3.8	2.3	18.3	15.9
RM9	29.6	20.3	9.3	2.6	14.6	12.0
RM10	30.1	21.6	8.5	2.5	11.5	8.9

Highest Value
Lowest Value

Table 3.3 Zn percent composition comparison and repeatability results for red and yellow brass samples.

High temperature and corrosion resistant scrap

Stainless Steel Alloys

Stainless Steel is primarily an Fe-Cr-Ni combination alloy. Stainless also serves as a prime example of why assessing XRF and LIBS data quantitatively is a very delicate process. Figure 3.15 shows a comparison between XRF and LIBS appearing seemingly similar, but this is not an accurate depiction of what was presented in our findings. Table 3.4 calculates the range of the returned readings (max value-min value). COV is important in showing how often the data fluctuates but it doesn't show by how much; it wasn't until we assessed the high temperature and corrosion resistant alloys that large fluctuations were prominent. Earlier we discussed how significant even a percent difference can be, in Table 3.4 we see LIBS displaying many ranges in the double digits, up to a difference of 60%, which is not something that could be observed from merely observing the averages in Figure 3.15. Sample SS6, where we see the highest ranges from the LIBS instrumentation is especially interesting because the XRF instrumentation did surprisingly well given the sample's condition. Surface homogeneity has had an overwhelming influence on the results for all instruments up to this point, but here the XRF fared far better by comparison. Additionally, there were numerous cases where a non-value appeared, and these cases made it difficult to conclude whether or not LIBS is capable of identifying the elemental chemistries within the alloy. These fluctuations became more abundant when assessing Mo, Ti, and W. While Ti wasn't so much of a struggle for the XRF and LIBS instrumentation on 3 out of 4 Ti samples, more testing would need to be done if we wanted to draw any substantial conclusions. XRF and LIBS results couldn't be compared for our Mo and W samples because the goal of the study was to assess the technology across all the instruments and there were LIBS instruments that could not take readings– returning measurements of either "100%," "non-lib*," or "ND**." The mix of returned and non-numerical readings further support the significance of handhelds being operated by trained instructors; only they can determine which values to trust, what are the misreads, and whether a coating is concealing the entirety of the metal's identification.

* "Nonlib" translates to "not in library" for one of the instruments.

**ND means "Not Detected."

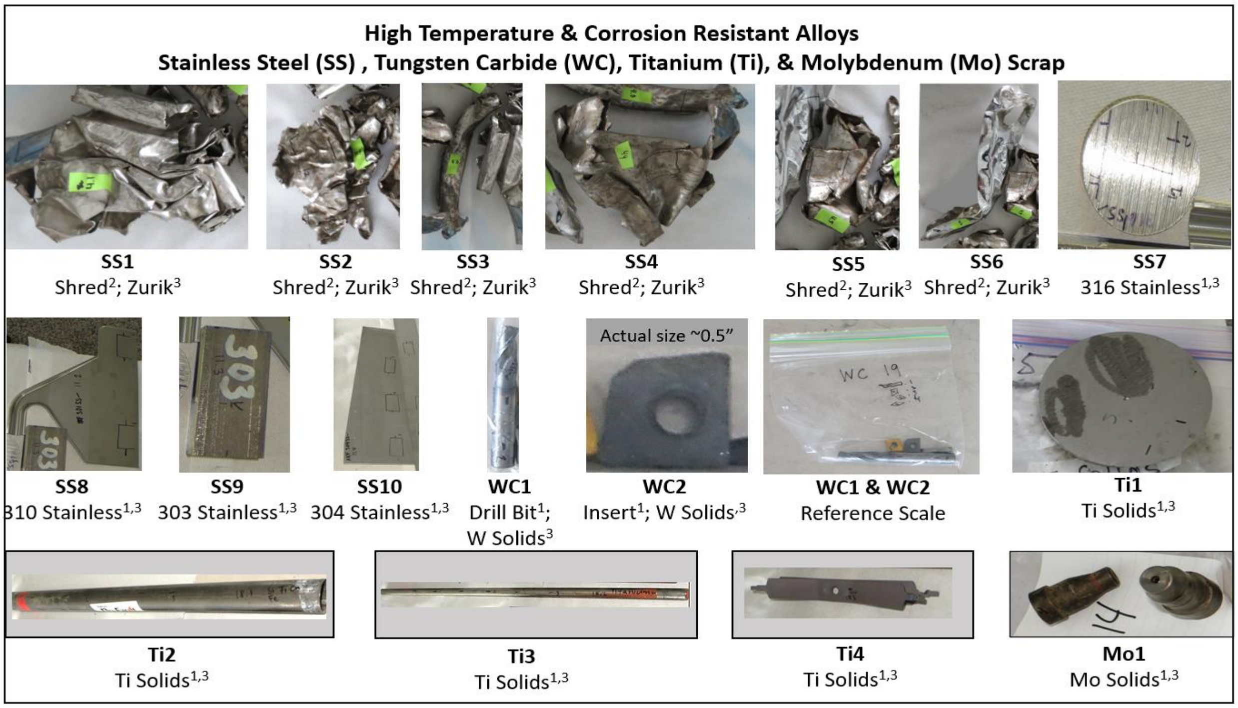


Figure 3.14 The graphic above is a collection of the stainless steel and other high temperature, corrosion resistant alloys obtained for our study. The Sample ID is accompanied by descriptors below (based off the condition of the image) and demonstrate the variety of ways these metals can be sorted. Superscripts indicate the following: original product[1]; how it will be proccessed[2] (or how it was processed prior to our collection of the sample); likely commodity grouped with[3]. Superscripts "2" and "3" depend on volume and equipment; if a "2" is not present, that means no processing required, if a "1" isn't present then the original product is unknown.

Figure 3.15 This is an example of how similar results can look if only assessed quantitatively when they are in fact very different.

Reading Ranges for Stainless Steel Alloys

	Fe (%)		Cr (%)		Ni (%)	
	XRF	LIBS	XRF	LIBS	XRF	LIBS
SS1	2.7	9.1	0.9	7.1	0.6	2.7
SS2	5.3	13.0	1.2	6.8	1.0	4.0
SS3	4.3	16.6	1.5	6.7	1.2	4.2
SS4	6.9	11.8	3.1	5.1	2.2	6.8
SS5	3.7	15.0	2.5	11.5	2.2	3.9
SS6	5.8	7.3	1.6	49.4	13.2	60.0

Table 3.4 Numbers demonstrate the delta between min and max readings returned for the same sample for major alloying elements in SS alloys.

Lead (Pb)

The findings that derived from testing various forms of lead using LIBS and XRF handhelds (sample images in Figure 3.16) were anticipated given their response to other heavy metals such as W(Z=74) and Mo (Z=42). The LIBS in many heavy metal cases cannot interpret anything other than the top layer (if at all). The LIBS instrumentation returned some readings of "100%" Mo and "100%" W in the results for high temp and corrosion resistant alloys but in the case of Pb, a much higher atomic number (Z=82), **all** returned readings across **all** LIBS instruments were seen to be "100%." This implies that the samples were free of trace metals and contaminants however, differences in the elemental chemistry of the lead samples could be seen on all XRF instrumentation, and not a single measurement expressed 100% Pb. Trace antimony, iron, silicon, and aluminum were among some of the highest element percentages found within the XRF results, but trace copper, zinc, and phosphorous were seen as well.

Although the LIBS HHs could not identify the trace elements, its ability to confirm lead is still extremely significant and should not be overlooked. Without having much experience and/or just observing samples like the ones in Figure 3.16, you can see how easy it could be to visually confuse these for steel or aluminum. Identifying these scraps as lead is invaluable to smelters, for if they end up in the melt they can produce extremely hazardous fumes and endanger workers. Therefore, both XRF and LIBS pose a substantial benefit to ferrous and non-ferrous operations for identifying the presence of a highly problematic metal.

Figure 3.16 Above are various forms of lead that were examined in our study. Superscripts are applied in the same manner as in previous sections.

Coated scrap

Ferrous and Nonferrous Alloys

Surface coatings come in many forms and appear on all metal types; examples of scrap with a variety of coatings can be observed in Figure 3.17. These inevitably are going to interfere with measurement readings for both XRF and LIBS because the thickness of the coating often exceeds the penetration depth for the instruments. Figure 3.18 uses pie charts to emphasize just how difficult identification can be when instruments have to overcome these barriers. It is because of these barriers that quantitative analysis can be exasperating. Sometimes instruments don't struggle, and you get what can be seen as a reasonable reading, but sometimes, mostly in the cases of XRF, you'll get a reading that is 50% less than what it should be. LIBS has its own set of challenges, whether it be simply not taking a reading at all, returning a non-numerical value, and/or returning a value of "100%" (because it is not capable of penetrating the top layer). The degree of complication contamination poses on developing technology for scrap identification is made clear in that although LIBS has the ability to utilize and increase the number of *cleaning shots*, it doesn't prove to be very effective in a lot of these cases. Not to mention, the additional "fires" cause you to have to clean the detector more frequently and drain the battery (and argon if the instrument uses it) more quickly— large inconveniences to any scrap yard laborer.

The most significant take away from the results below, are the numerous instances where LIBS instrumentation could not perform a measurement at all or assumed 100% composition of an element. Plating, coatings, and other forms of contamination interfere with XRF results by fluctuating the distribution of percent composition by weight, but they did not prevent the XRF instruments from returning values. Table 3.5 goes over the different types of coatings and the elements associated with them. This is helpful for anyone using this type of instrumentation to know and understand because when compositional windows are off, these are things you can verify as the culprit and correct for. In these instances where surface contamination causes significant interference, it would take a trained operator to understand that the reading being displayed is not representative of the metal in its entirety. Additionally, circumstances like these make the instrument more vulnerable to overlapping spectra, leading to readings of elements that are not in fact present. For these types of cases, automated inspection would fail and therefore demonstrates that visual inspection, to some degree, will always be necessary.

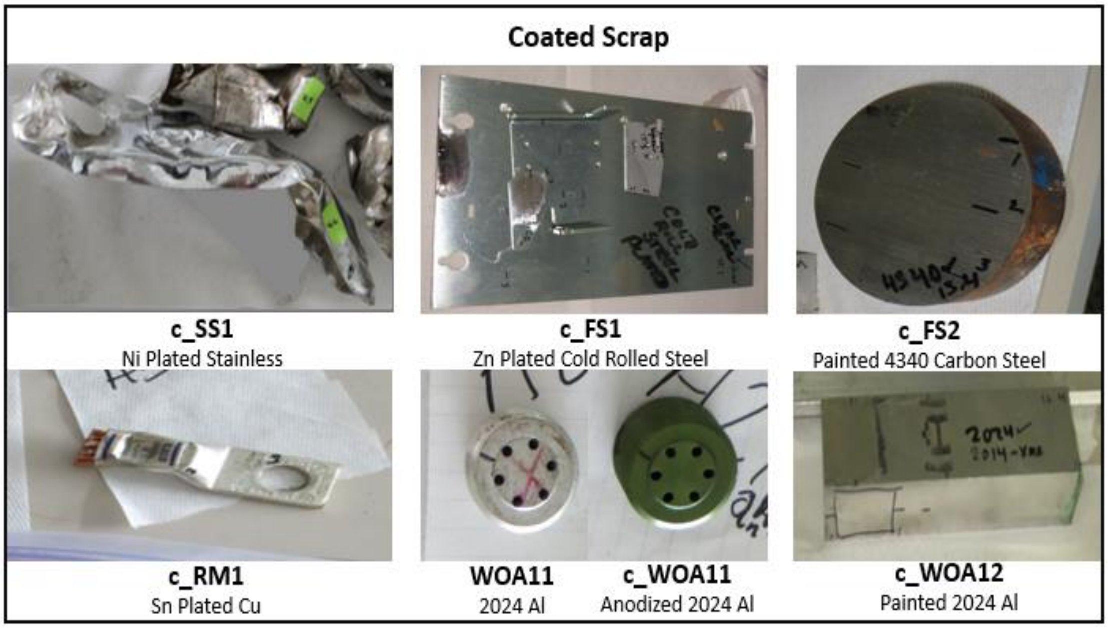


Figure 3.17 Surface coatings can appear in many different versions and thicknesses; they include (but are not limited to) things such as plating (e.g. Zn, Sn), varnish, and paint. The above samples are examples of the different potential layers that inspectors and technology must be able to identify beyond in order to verify the metal beneath/within. Descriptions below sample ID are to clarify what the surface coating on the scrap we are assessing, not necessarily how it would be sorted like in the previous sections.

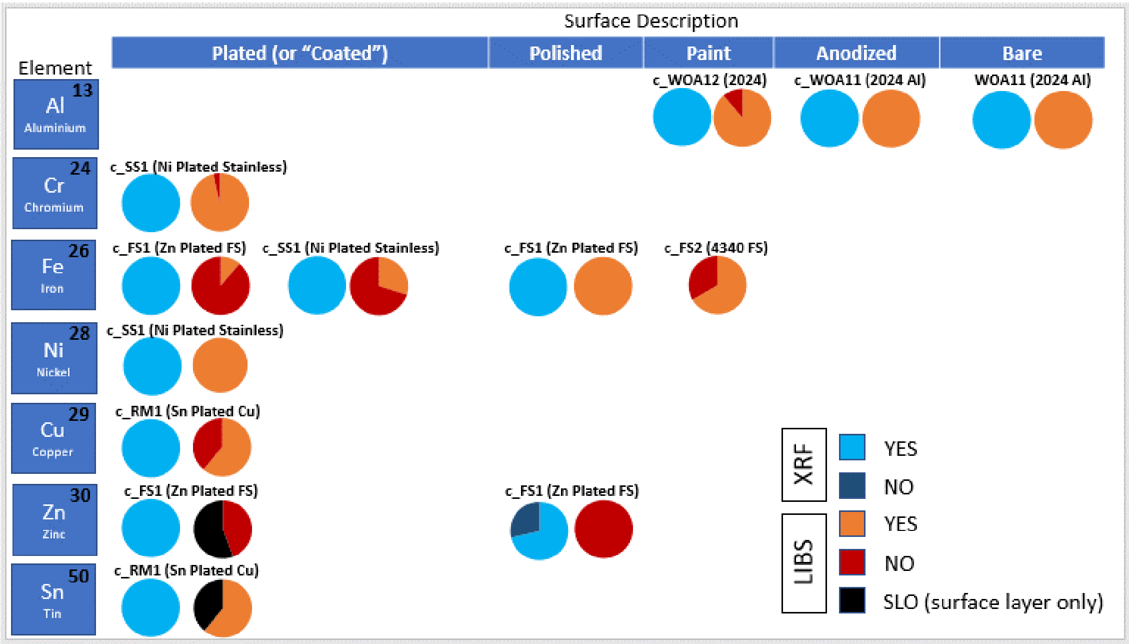


Figure 3.18. Pie charts are a representation of how capable the instruments were in reading the chemistry of the sample with particular surfaces (surface description on top row). Pie charts are grouped in pairs with XRF in blue color variations to the left and LIBS with red/orange variations on the right. The sample IDs are indicated above the pairs with the element being assessed in the column on the far left (elements arranged by atomic number, in ascending order). A "Yes" means a numerical measurement was returned when taking the reading. A "No" was given for any reading where a reasonable measurement wasn't observed; this includes instances when the instrument simply would not take a reading as well as returns of "ND" (not detected), nonlibs*, "<LOD"**, and/or "0.0."

* "Nonlib" translates to "not in library" for one of the instruments.

**"<LOD" means the % composition of the element in question is less than the limits of detection.

*** The lone c_FS2 pie is because circumstances didn't allow for us to get enough readings across the XRF instruments

		Surface Coating and Contamination Culprits								
		Dirt	Galvanized	Grinding	Insulation	Paint	Plasma/ Electrical Discharge	Rust	Sand Blasting	Varnish
Atomic #	Element									
12	Mg	×								
13	Al	×		×						
14	Si	×		×	×				×	×
15	P									×
16	S									×
22	Ti					×				
24	Cr					×				
26	Fe							×	×	
29	Cu						×			
30	Zn		×				×			
40	Zr			×						
82	Pb					×				

Table 3.5 The table above gives examples of the different types of coatings and contamination atop scrap along with the elements that are typically associated with them that often prove troublesome for PMI.

3.5 Conclusions

Integrated techniques, those that are high volume and physical property (of the metal) focused, are frequently designed to be updated with new and/or improved technologies in mind and are an effective initial step in what can often seem like an overwhelming undertaking. They are advantageous in that they can handle large quantities and many forms of material quickly. However, the equipment is expensive and so are the “add-ons” and/or ‘upgrades’ plus, the “scrap gap” has still not been addressed with these techniques. At best, we can obtain fractions of the feed divvied up according to base metal (i.e. red metal, Al wrought alloys, Al cast alloys, lead, stainless, iron, etc.) which is good and bad. Good because we have in fact segregated the metals by type, but not so good in that we have now grouped together similar looking metals that are extremely difficult to decipher from one another; thereby reverting us back to relying on visual inspection as our main option for further identification. *Laboratory scale technologies* are a reliable resource for PMI testing. Unfortunately, they are not favored nor practical for regularly needed identification, and sporadic testing doesn’t warrant the cost to own the instrument. Both integrated and laboratory equipment can range from tens of thousands to millions of dollars to manufacture and assemble. Additionally, video demonstrations are rarely representative of how the equipment will function under conditions specific to the intended buyer’s yard (because every yard is different and receives a different balance of material quantities). Not to mention, downtimes, due to repair and/or maintenance, delay processing and lead to extremely high costs that weren’t anticipated. Thus, it is incredibly risky for yards to make such purchases because unlike most things in today's society there aren't reviews or trial options, but even if there were, there is no way of knowing everything that will come into the yard and how that equipment will respond to it. Price has long been the ultimate driver and most management's aversion to change, if identification technology is to be truly successful in this industry it will need to take this and all previously stated variables into consideration.

Another critical component, is recognizing that identification technology developed for the purpose of characterizing scrap may not be able to escape the need for human confirmation and therefore should be designed to aid, not replace. All materials entering a yard are vulnerable to surface contamination and from our study we can see that no instrument, regardless of its ability to "fire" "cleaning shots," has the ability to completely overcome. Ergo, the level of interference between metal and instrument will need to be discerned through observations only a trained operator can make. Low equipment cost(s), instrument ergonomics, durability, and ease of sharing and documenting information are some of the key aspects handheld analyzer manufacturers advertise outside LODs, precision, and accuracy– for they appeal to the human component necessary for its use.

Handheld analyzers are not all created equally but they are getting impressively close. This study demonstrates that the majority of these instruments will in fact identify what it is in front of them or it won't take a measurement at all—eliminating, to a degree, false positives of identification. Interference by particular elements will and can persuade chemistry percent fluctuations, making designation by alloy name (grade matching) unlikely. Nevertheless, if alloy modes are set correctly, it shouldn't report an element that it didn't actually detect. This should not be misconstrued as an assertion that the chemical composition it returns should be accepted blindly which is why trained inspectors are key to its success. Well-trained operators are needed for these instruments, just as there are trained operators supervising *integrated* and *laboratory techniques*. A trained shredder operator knows that their shredder won't be able to process certain material without it negatively impacting the motor and/or its blades. The same expectations should [and do] fall on the operator of a handheld analyzer—they must be able to recognize that an analyzer reading of 100% zinc [for instance] may just be a coating, and to get an accurate read they will need to grind/file beyond the surface layer. Additionally, the results in Section 3.4 illustrate that when and if operating with a LIBS HH rather than XRF on especially high temperature alloys, like tungsten, lead, and molybdenum, LIBS struggles identifying beyond the base metal. Consequently, if a more detailed chemistry is pertinent to their buyer, these are the types of instances that will require inspectors to have to choose specifically XRF over LIBS (and vice versa with alternative metals). Cases where you have something specific or more advanced you want the HH to analyze (e.g. trace elements in Pb), are possible with handhelds through customizations and/or modifications; alterations allow inspectors to assess certain chemistries where lower LODs for particular elements in specified metals are desired. Subsequently, if there is a main intent for your instrument, and that is to perform an analyses one or the other technology is not capable of, as opposed to a general across the board ability to identify various metals, you can often cut costs by ordering equipment to fit that specific need. Instruments with a less extensive grade library often equate to a lower purchase price, which then also makes it more feasible to own both an XRF and LIBS (a general use instrument and a specific use one). Although needs such as these are more commonly seen as the needs of secondary metal producers such as mills, foundries, ingot makers, etc. than your standard scrap yard, niche yards are still abundant.

All these considerations plague an additional question – to what degree of identification is and will be necessary in the future? As seen in the results, sometimes chemistries are off. This may be due to surface contamination, but it could also very well be due to the fact that shredders and other potential processing equipment are altering the actual composition of the metal; processing mixed miscellaneous metals on the same conveyer can lead to metals merging by the same forces being used to sort them. Handling high volumes [efficiently] requires some initial processing which then also means alloy matching isn't always going to be possible (b/c that alloy has been transformed). Therefore, we may need to re-think sorting and separating to be based on, or additionally consider, contamination levels for a particular metal (e.g. Fe, Si, Mg, in Al and Cu in Fe). The results above and current industry conditions reveal that handhelds focusing on being able to "grade match" may not be what we need from them but rather making sure minimums are kept and maximums aren't exceeded for particular elements (per whatever the secondary metal processor's needs are), because it's these levels that influence how much primary material is needed for diluting (or blending). The utilization of technology to identify chemistries in scrap sorting has an understated significance— dilution is a mitigation tactic therefore, without extended producer responsibility and product design considerations, chemical identification-based sorting is the only **preventative** tactic we can employ to improve scrap utilization rates in the production of new goods. Handheld analyzers are at the point where they are a low risk, low cost (by comparison), high reward instrument. In the hands of a trained inspector, they can guarantee [again, if used correctly] not only a reduction in losses from wrongful identification but increased profits from sorting out difficult to identify metals that are of greater value; as opposed to downcycling or comingling because it's too difficult and time consuming to segregate. Identification and inspection have to be a process, not a one and done, we will need the right balance of technology and well-trained workers to accomplish this feat.

Chapter 4

Quantifying the Benefits of Identification and Sorting Technologies for Improving Scrap Yard Operations

4.1 Introduction

A comprehensive cost-benefit analysis for identification and sorting technologies applied to metals recycling requires knowing the key cost influencing variables in yards and smelters. In Chapter 2, we learned the challenges that yards face every day and their current and past limitations to addressing them. Additionally provided, is a thorough analysis evaluating the technologies that exist, which processes they can be applied to, and the level of assistance they have the potential to offer. Chapter 3 then takes this information to build a case study, testing some of the latest advancements in identification being advertised to the industry in the form of XRF and LIBS handheld analyzers. The study evaluates their potential for practical in-field use and reveals, quantitatively and qualitatively, the difference between how these instruments perform in a lab, and what is happening when applied to the actual types of scrap samples that the industry handles.

The results from Chapters 2 and 3 give us the knowledge and the know-how to build a technoeconomic model that reflects the financial realities of the yard and the range of performance of the equipment when applied to these processes explicitly. Cost-benefit analyses (CBAs) and technoeconomic assessments (TEAs) for technologies for ferrous and nonferrous recycling operations are rarely published as such data is considered proprietary. Some manufacturers of the reviewed technologies provide estimates of cost savings given certain through-puts. Scrap processors across the country were solicited for their input on their experiences with purchasing new equipment; specifically, sorting and identification technologies (material handling equipment such as forklifts and front loaders were excluded from this analysis). They were asked what was the described outcome that the manufacturer(s) presented, how the equipment performed once installed on-site, and what they thought was preventing the equipment from operating to its full potential. Although most were pleased with their purchase (i.e., they didn't return it), 100% stated it did not work in-field as advertised but, very few had the expectation that it would. Other than the proprietary internal company analyses and the "takeaways" manufacturers promote, techno-economic assessments found in literature, under the waste management and recycling sector, are "waste" category specific. For instance, a significant body of research exists examining construction and demolition waste (CDW or C&D) sorting and comminution technologies (Cimpan et al., 2016; Oliveira Neto et al., 2017; Yuan et al., 2011), and numerous case studies involving municipal solid waste (MSW) advancements and the performance of their management systems in different countries (Athanassiou &

Zabaniotou, 2008; Weng & Fujiwara, 2011). There are also several TEAs evaluating the economics and environmental costs and benefits of whether it is *worth* recycling certain materials like plastics (Larrain et al., 2021; Volk et al., 2021), electronics (WEEE) (PĂCESILĂ et al., 2015), batteries (Wang et al., 2014), and metals, especially in valuations of urban vs. virgin mining (Zeng et al., 2021).

It is challenging for the scrap industry to understand under what conditions a technology intervention may be financially worthwhile. This work aims to overcome this gap via a technoeconomic assessment model. The model not only addresses parameters that help evaluate true performance on-site, but it quantifies the environmental benefit in terms of the profits that result from producing cleaner scrap streams. Additionally, the identification and sorting techno-economic assessments not only explore the different performance levels in terms of volume and capacity but examine different sorting approaches to determine if a profit-driven approach can produce a positive environmental outcome in the form of decreased downcycling and comingling. Actions taken by yards such as downcycling and comingling yield a product of mixed non-like metals consisting of different compositional specifications, resulting in products of lesser value and the accumulation of impurities. Subsequently, such practices limit scrap utilization rates, and require the addition of primary ore (for dilution), preventing many of the positive benefits from recycling to be realized. Downcycling and comingling can happen on purpose or by accident due to incorrect identification and/or lack of resources for alternative sorting options. As emphasized in all previous chapters, materials don't enter yards in the form they need to leave in, they are mixed, similar in appearance, and extensive sorting can be an overwhelming undertaking. Unfortunately, but unsurprisingly, many recyclers equate more involved processes to a cost and/or time burden, which means in the absence of advanced, affordable technology, these actions will remain.

The first step taken by the yard to determine if new equipment is worth exploring includes an evaluation of the physical cost of the equipment and its installation. Also taken into consideration is depreciation, the cost of the material, and what they can sell it for under current market conditions. Cost of labor and estimated volumes through the equipment are also considered in the initial analysis. Prior to seeking equipment and advanced technology options, they need to identify a potential competitive advantage that could be had if a given capability existed and/or acknowledge a growing challenge that if not proactive about could put them at a disadvantage. Presently, aluminum fulfills both preconditions. As aluminum usage and alloy diversity continues to rise, especially in the transportation industry with the increased production of light weight vehicles, there is a growing demand and need by the yards for the ability to separate and identify these alloys. Identification confirmation through visual inspection relies heavily on the ability to recognize an alloy by knowing what it is used for, but manufacturers are now using multiple alloys for similar items, which is transitioning identification from certainty to assumption. This uncertainty when separating not only threatens to increase the volume of current types comingled packages, but it has the potential to create new ones. This model will use both quantitative and qualitative information to determine not only the ways technologically advanced equipment can be utilized to improve processes but, if and to what degree it makes economic sense. This analysis is unique in that it is more than an evaluation of return on investment (ROI). The assessments evaluate different equipment that offer varying levels of improved identification and sorting capabilities, and the time and volumes that correlates with each level. This distinction will give insight as to what opportunity cost can be associated with what level of sorting, in an attempt to determine whether producing cleaner streams (reducing comingling) is an affordable and profitable option. Below is an extensive look at key variables that must be addressed in any scrap yard CBA, for they are also what influences a recycler's desire and need for advanced technologies and equipment.

Costs of contamination

Scrap yards receive materials from several different types of accounts: industrial, commercial, and individuals (also known as peddlers). These suppliers may have like-materials they bring in (e.g., plumbers often bring in copper tubing) or mixed miscellaneous metals (e.g., a construction company may have steel, aluminum, electronics, and insulated wire). Unless the customer is producing high volumes of one very specific type of scrap, the likelier scenario is that materials will be delivered mixed in a van trailer or roll-off container. Mixed loads from smaller scrap yards are also typical, they are usually delivered by van trailers, often separated by base metal (in gaylord boxes on pallets), or by application (e.g. radiators, electric motors) but still require further identification, sorting, and/or processing. There a few ways this service of sorting for the customer can be done and each result in a different cost-benefit outcome. Here are some examples of options account managers can offer to their suppliers in the case of receiving materials mixed: (1) a fee for sorting, separating, and reweighing is charged to the customer, and they are later paid based off a "sort report" for their scrap, (2) a visual inspection of the material prior to delivery and offering a price that factors in their estimate of contamination and labor involved for processing. or (3) the customer agrees to commit their scrap to the company in exchange for not being charged for the service of being provided with a bin where the recyclables can be collected on-site (that is picked up and replaced upon request). In the case of the "sort report" method, any contamination found is deducted from the total amount of money owed to the customer based on the contents of the materials shipped. In many other cases, yards simply expect a minimum of 1% contamination and figure it into their pricing for the material they have agreed to purchase. Contamination of greater than 1% will typically be charged back to the supplier. Generally, the amount of contamination considered acceptable by the yard will be explicitly stated and agreed upon in contracts that have been established between the buyer and seller beforehand. One percent adds up quickly, especially when that 1% is attached to multiple loads of 42,000lbs (a fully loaded truck). In most cases, contamination turns into landfill feed and thus, tipping fees must be included in any techno-economic assessment (these vary based on location).

Contamination can come in the form of non-metallics (e.g. plastic, moisture, oil, cement, wood), mixed metals of different base metals (e.g. iron in aluminum, lead or iron in copper, or copper in iron), or even alloys of the same base metal (e.g. 2xxx & 7xxx series aluminum mixed with 3xxx, 5xxx, & 6xxx series aluminum or even mixing a 6061 aluminum alloy with a 6063 aluminum alloy). Not only is the amount of contamination stated in the contracts between buyer and seller, but so too are the materials considered to be contaminants. Regardless of communication efforts, certainty is hard to achieve as unwanted materials inevitably slip through. Consult Waste Management's review article, Ferrous and Nonferrous Recycling: Challenges and Potential Technology Solutions (Brooks et al., 2019) (or see Chapter 1) for a lengthier discussion of contamination.

Markets and commodities

Understanding where a metal's value comes from, and why, how, and when that can change is fundamental to owning a scrap operation. This allows you to receive fair pricing for your materials and in return, offer a fair price to your customers. There are a handful of considerations that are taken to price material, but this is first to influence what processes will come next. Starting with the basics, commodity pricing is a derivative of supply and demand and an indicator of market conditions; it is what defines the intrinsic value of individual metals and their alloys. Ferrous materials like steel make up the majority of recycled scrap metal by weight, but they are on the lower end monetarily; aluminum is approximately 7 to 8 times greater in value than that of steel, while copper is 3 to 4 times greater than that of aluminum. This is essentially what incentivizes recyclers to process and breakdown materials into their most basic components, for everything is worth more in its purest form. Market conditions for this industry are often volatile with many influencing factors such as natural disasters, global pandemics, and trade relations with foreign countries, especially China. There are also ways that computer algorithms can influence market prices, in addition to the effects caused by people choosing to hoard material, but detailed discussions of these two particular influences are outside the scope of this paper (Brown & MacKay, 2021). Moreover, every type of material that comes in requires a different style and/or level of involvement to process. There are different methods for liberating individual metals, making size reductions (to make the material "smelter-ready"), and for packaging and processing. The difficult measures the yard must assume in order to process, sort, and separate the material will impact their margin and therefore, these costs must be incorporated in how the material is priced. Instruction for how to sort the material will be determined primarily by evaluating the safety risks, volume of the feed(s), the equipment that is available, and the level of knowledge and training that can be reasonably expected of the employees responsible for handling. These types of considerations all have associated costs:

1) Smaller volumes of material, usually fewer than 1,000 lbs, are paid pennies less per pound.
2) Needing a more skilled and knowledgeable worker means paying more for labor.
3) Not having certain equipment may mean having to outsource jobs or find an alternative way to process or sell the material.

Safety costs

The aforementioned safety concerns and hazards are another area where costs can add up directly and indirectly. For this reason, these costs can be difficult to quantify and/or generalize but what’s more, is they will also vary based on the equipment, the type of material accepted into the yard, and geography. Some examples of this include costs expended for extensive safety mechanisms and readily available PPE such as gloves, steel-toed boots, and hard hats. Also costly, is worker’s compensation, insurance policies for fires and various equipment, and even a poor safety record can lead to long-term financial losses. The dangers lurking in scrap yards cannot be overstated. There are risks directly to the workers’ health and safety, as well as the environment, customers, the cities they operate in, and the next in line to receive the material once it leaves the yard. One of the top areas of concern stems from operating equipment or being near equipment that is mobile or has moving parts. Forklifts are key to any scrap operation and are also extremely dangerous. In the latest data from the U.S. Bureau of Labor Statistics, in the year 2017 there were 74 deaths and 9,050 accidents involving forklifts ("Occupational Injuries, Illnesses, and Fatalities Involving Forklifts," 2021). Other areas of high concern are not locking out equipment properly, slips and falls, and being struck by or caught in equipment ("Guidance for the Identification and Control of Safety and Health Hazards in Metal Scrap Recycling," 2008; *Recycling | Scrap Metal Recycling | Occupational Safety and Health Administration*, 2021). The mass volumes of mixed miscellaneous materials necessitate thorough inbound inspection, as well as highly attentive supervision and dutiful, well-trained labor. One of the prime reasons for this is because materials that can pose serious threats are not always ones that are easily noticeable. For example, internal components like light ballasts, can contain harmful PCBs. Sealed units not drained nor stored properly can leak oil. Closed canisters and lithium-ion batteries can cause fires and lead to explosions. Additionally, there are materials such as insulated copper wire (ICW) that could contain lead (Pb). If this not properly separated and sorted out from the copper, it can produce dangerous fumes if it is melted in a secondary producer’s furnace. Lastly, shipments to smelters of aluminum loads containing excess moisture can lead to deadly furnace explosions (Epstein, 2009; "Guidance for the Identification and Control of Safety and Health Hazards in Metal Scrap Recycling," 2008; M. D. Bertram').

Geography and freight

Geography and freight are an extremely important part of any scrap operation's cost considerations. The location of the yard can heavily influence what is likely to come across the scale, in other words, the feeds that can be expected and what type of customer base is likely. Freight is known as "what can make or break you." Transportation costs fluctuate often thus, how far the material needs to travel to get to you or to get from your facility to the buyer, such as a secondary smelter or larger yard, needs to always be considered in the margins when pricing materials. Additionally, it is in this area where rejections get pricey – sending your material to a facility that declines your shipment, likely due to contamination issues, means the material must return to your facility for further processing before being shipped back out again. These costs can be very damaging to the bottom line. Moreover, the cost of transportation (trucking, rail, and ocean containers) has been increasing over the past 15 years, which additionally impacts profitability [expert solicitation].

Yard type and overhead

Overhead considerations for every yard are a must. This amount will be very specific to each individual facility and will also change drastically based on the state and their location in that state. Overhead categories include, but are not limited to, costs to own and operate (rent), electricity, and any staff that are subject to salary pay. The most challenging to predict and model are costs of maintenance and the different types of insurance (FreshBooks, 2021). These are some of the variables that fluctuate based on location and the on-site equipment; determining a value to assign them in a model is quite complex. In regards to insurance, yards generally need to consider worker compensation costs, general liability, fire, and business interruption; equipment has its own [separate] insurance [expert solicitation].

The type of yard you are managing is going to determine the materials being received and how the materials are to be shipped. Many yards today started only purchasing ferrous materials but have now realized the opportunities nonferrous presents. It cannot be emphasized enough how different ferrous and nonferrous processes, equipment, training, and customer base (for purchasing and selling) are alone. Not to mention, each come with different sets of contaminants and safety regulations.

A scrap yard's desired outcome (or motivation) is another important aspect of how materials will be processed, sorted, and sold, and directly impacts profit and loss. In other words, an operation might change its processes if they have time constraints, like filling orders specified in a contract between the buyer and seller. Another option yards have is deciding that they want a simple yard where they don't have to do a lot of processing, they can just collect materials until they have a large enough volume to sell to someone else for handling. Others might aim to try to move as much volume as quickly as possible, this would be a mentality suited for a shredder operation. Then there are yards that care significantly about the types of processes they want to use, how the end-product is achieved, and prioritizing safe working conditions. And of course, there are yard versions that are a mix of all previously described.

4.2 Methodology

Aluminum scrap sorting and identification

Aluminum can be broken down into 2 overarching classifications, cast and wrought, our focus will be on the latter. Wrought alloys consist of 9 different series that are designated based on their alloying element (See Table 4.1). These different alloying elements give aluminum unique properties that allow it to be useful and safe in various applications. The table below provides a few application examples however, as you can see, some of those examples fit into other alloy groups as well. For instance, aircraft parts can be made with a 2xxx series or 7xxx series and automotive parts can be made with 5xxx series or 6xxx series; but these designations also do not mean that certain parts today are not made using other alloy series. According to the Aluminum Association, there are now >531 designated aluminum alloys, up from 75 in 1954 (The Aluminum Association, 2020). Due to the copious amounts of alloys there are to sort, scrap yards have mixed/comingled packages, which are often based on the commodities identified in the ISRI Scrap Specification Circular. MLC, short for "Mixed Low Copper," consists of 2 or more alloys but must be free of 2xxx series and 7xxx series (*ISRI Scrap Specifications Circular*). As the automotive industry continues to significantly increase their aluminum usage, which was 324lbs (147kg) in 2007, up from ~81lbs (36kg) in 1973, to an estimate of 650lbs in 2020, it is not surprising that yards are seeing and will continue to see large influxes of mixed aluminum alloys (Benedyk, 2010). A particular area of interest is working to be able to segregate/differentiate the 5xxx series from the 6xxx series, a challenge for visual inspection and most technology. Therefore, we will aim to find what value lies in being able to segregate these alloys from each other as opposed to comingling them in an MLC package.

Wrought Aluminum (Al) Alloy Groups			
Series	Major Alloying Element	Heat Treatable Y/N	Examples of Common Applications
1xxx	Unalloyed Al ≥ 99%	-	Electrical conduit wire (1350), food packaging trays, & lithographic Sheet (1100)
2xxx	Copper	Y	Aircraft parts (2024)
3xxx	Manganese	N	Al [body of] beverage cans (3004; lid is different)
4xxx	Silicon	N	Welding applications
5xxx	Magnesium	N	Marine & architectual applications, electronics (5052), lid of Al beverage can (5182), automotive parts
6xxx	Magnesium & Silicon	Y	Windows & door frames (6063), wheels (6061), automotive parts
7xxx	Zinc	Y	Aircraft parts (7050, 7075)
8xxx	Other Elements	-	Al sheet (8011)
9xxx	Unused Series	-	-

Table 4.1 This table identifies the different wrought aluminum (Al) alloy series, their major alloying element, and examples of some common applications. The 1st digit of the series (xxxx) defines the major alloying element, the 2nd digit (xxxx) specifies a minor modification made to a specific alloy (e.g. if that number is a 3, that means it's the 3rd modification). The last 2 digits (xxxx) are sequential numbers that the Aluminum Association has assigned to represent specific alloys that have been submitted to the association and meet all the registration criteria. The only series that is identified somewhat differently is the 1xxx series, where the last 2 digits signifies the additional percentage of the alloy that follows the decimal (i.e. electoral conduit wire is a 1350 alloy, meaning the minimum amount of Al in the 3rd modification of a 1050 alloy is 99.50%) (Haomei Aluminum, 2018; Lang, 2012; The Aluminum Association, 2020; United Aluminum, 2020).

Scenario considerations

Building a model that can give quantitative insight on the value of sorting and identification technologies will have to take into consideration all variables outlined in the introduction, combined with what has been learned from "The Potential for XRF and LIBS Handheld Analyzers to Perform Material Characterization in Scrap Yards," and research on the latest advancements in LIBS-conveyer system sorting. Perhaps the most difficult to quantify but also the essential foundation of the model is determining a baseline for technology comparisons, we have deemed this "Scenario A." Scenario A is handling material at its simplest level; delivered to the yard as a comingled package known as MLC and shipped out as the same package. However, as a part of the inspection process, material entering the yard must be inspected before shipping and as such, it is dumped, checked for non-metallics and various other forms of contamination (e.g. ferrous attachments) before being reloaded by hand into a separate container, and then shipped to a secondary processor, producer, or potentially a larger yard. This scenario considers a minimal amount of equipment and labor: 2 laborers picking up the dumped material by hand, throwing it into 2 metal hoppers, having an assigned forklift operator that picks up a hopper when full, empties it in an open top/roll-off container, and returns it back. This is a method of processing that could be expected to take place at a smaller facility, a start-up yard, or even a larger yard that is only generating small volumes. We will then assess the value of the most basic training, which will be inspecting for contamination and sorting out one commodity, while the rest remain comingled (slightly decreasing the processing speed but improving the package) (Scenario B). Next, we will look at using handheld analyzers, which will be the assessment that is expected to most emphasize the value of identification technology, because we will be able to examine the ability for an alloy-specific sort but at a much slower speed (least volume per hour) (Scenario C). The Steinert LSS assessment will follow, representing our high-end, most costly nonferrous technology, but most promising if capabilities prove true (Scenario D). The Steinert LSS is a conveyer LIBS system, that as advertised claims the ability to sort Al by alloy type including the 5xxx series from the 6xxx series. The Nonferrous Steinert Model Standard Series best handles widths from 500 to 2500 mm; 16”- 80” while the S50 and S61 models are said to be able to manage smaller widths >5mm and 1-20mm respectively. Lastly, is the assessment of a high-speed capacity shredder (Scenario E). This will be done to emphasize the range in outcomes from processing ferrous rather than nonferrous. Ferrous materials are in the ten-cent range while aluminum is worth around sixty cents more; but, with ferrous materials you can typically process at 10 times the speed, a volume that far exceeds any nonferrous equipment capabilities.

To simplify, all pricing in the model is either quoted as a delivered price when purchased by the yard and a picked-up price when sold from the yard. This is often how material is priced but the model does it this way because yards can have multiple places near and far they send material to, and if the price is already incorporating freight, it becomes redundant to add it in as a variable (see Table 3 for additional assumptions the model makes). Although, because the material is assumed to be loaded loose, we do account for an additional underweight charge of $0.01/lb for each 10K lbs. that is under what is considered a full weight (greater than 40K lbs). For all scenarios we first determined the processing rate and maximum capacity for a full month’s operation hours (10hr shift/person x 22 shifts/mo = 220 operating hrs/person/mo). These numbers determine how much material can be processed per month. Scenario descriptions and details can be found in Table 4.2, model assumptions are summarized in Table 4.3.

Scenario	Description	Details
A	Comingled (Baseline)	Dump, inspect, remove 1% non-metallics
B	Sort out 63 (Basic Identification Training)	Recover all the easy to identify 6063 (~31%), the rest remains comingled (MLC), remove 1% non-metallics
C	Handheld-Analyzers (HHs)	Use HHs to sort out 5 different alloys, remove 1% non-metallics, assume 5% remains comingled (MLC)
D	Steinert LSS LIBS	High speed sorting of 5 different alloys, 1% non-metallics, assume 10% error (amount of material that remains comingled)
E	High-Capacity Shredder	High capacity, high speed shredder for ferrous, nonferrous comparison

Table 4.2 Summary of scenarios modeled

Assumptions	Details
Material is being shipped loose	Loose Al is only going to be around 30,000lbs which adds an additional .01 to your freight costs could added into model as a charge of $0.01/lb. for being underweight
Other than the above freight charge, freight is figured into the price	Prices are assumed delivered for purchases and picked up for sales
Model assumes sales prices are fixed or already contracts for sales	Market conditions can change from when you purchase something to when you go to sell it. Model looks at different markets and changes in commodity prices to account for this
$0.01/lb in overhead	$0.01/lb is subtracted from the profit margin to acknowledge the costs of overhead
Instrumentation has been calibrated for the specific alloys that are being pulled out	Still accounting for some uncertainty with instrumentation by including a 5% error with the HHs (comingled), and 10%-100% for Steinert
Above average errors	Most manufacturers claim optimistically high recovery rates but this extremely hard to achieve in a scrap yard

Table 4.3 Summary of model assumptions

Markets and commodities

Scrap yards hire Account Managers to travel to different regions sourcing and buying material to be delivered into the yard. In order to have a competitive advantage, these Account Managers must also understand how to best market various materials once they accumulate to “truck-load” quantities to increase the number of potential buyers when they are ready to sell. This iterative process of obtaining customers and buyers is done through learning how to speculate market conditions of different metals and the associated commodities affected by them; which often equates to constant monitoring of multiple different markets throughout the course of the day, every day. Two of the most common choices amongst many recyclers for nonferrous metals are the London Metal Exchange (LME) and the domestic Commodity Exchange known as COMEX. The LME has been around since the 19th century and today, it specifically caters to the metals industry (*London Metal Exchange: History*, 2020). Primary aluminum was one of the most recent commodities that the LME added on their list of contracts traded, but since then, it is a highly common reference for pricing among the scrap community (*London Metal Exchange: History*, 2020). COMEX, an exchange in the CME Group Inc. marketplace, is a common choice for trading copper futures, and therefore a great source for copper pricing and information (*Copper Futures*, 2021).

As mentioned in the introduction, this study will focus primarily on technology intended for improving aluminum scrap identification and sorting, specifically a commodity package known as "MLC." Aluminum MLC ISRI Specification is defined as "new, clean, uncoated and unpainted low copper aluminum scrap of two or more alloys with a minimum thickness of 0.015" and to be free of 2xxx and 7xxx series, hair wire, wire screen, punchings less 1/2" diameter, dirt, and other non-metallic items. Grease and oil not to total more than 1% Variations to this specification should be agreed upon prior to shipment between buyer and seller" (*ISRI Scrap Specifications Circular*). Alloys we aim to sort out are 5052, 6061, and 6063. Additionally, we have a miscellaneous 5xxx ("misc 5xxx") and a miscellaneous 6xxx ("misc 6xxx"). Scrap pricing for the listed commodities was obtained from the LME (3Mo). Each month's historical pricing was then averaged, where the misc. 5xxx was always priced at .10 below 5052, and the misc. 6xxx was priced at .03 above 6061. The pricing that was used for the alloys characterized by "misc." were based on a proprietary case study and that is why the specific alloy names cannot be referenced. Although labeled "misc.," they are still representative of other 5xxx and 6xxx that are priced in a similar range and the marginal spread below 5052 and above 6061 were consistent in different markets by the amount specified above. It is more significant to point out 5052, 6061, and 6063 because these are some of the first aluminum alloys that individuals are trained to identify and segregate, and often represent 50% or greater of the aluminum volume that yards receive (unless they have unique accounts that generate a large volume of a less common alloy). Due to an increase in the production of like-products with the same alloy [which complicates identification tactics], and the several additional misc. 5xxx and 6xxx that are being used for light weighting vehicles, we are ultimately seeking what would result if we could deploy identification and separation technology to sort 5xxx from other 5xxx, 5xxx from 6xxx, and 6xxx from other 6xxx.

The scrap and commodity pricing assessed within this study was derived from the Argus database, a trusted resource for past, present, and future data across different markets. We exported London Metal Exchange (LME) and COMEX market and scrap commodity values from 2010-2020. Next, all data points in a month's period were averaged to determine a single value representative of that month and year. These commodities and their primary metal market value were then graphed alongside each other. Once we had all the values graphed, we were able to look for interesting changes in market conditions and how the commodities varied in relationship to those changes. To demonstrate how difficult and unpredictable aluminum markets can be not only over time but from other secondary markets we collected data over a 10-year period for copper to give an idea of how markets compare and differ (this information is what was extracted from the COMEX market).

Total volume and volume distribution

Revisiting the goal of determining which conditions support owning expensive equipment we need to consider what will happen if the percent error of the equipment increases, or the volumes being processed by the equipment are less than expected and potential downtimes. Manufacturers may advertise their equipment as having a 99.5% recovery rate, but this is only under perfect conditions, which in a yard are statistically extremely rare. Thus, for Scenario D we started our evaluation for the max amount of volume that can be processed given the processing speed of the equipment (2 tons/hr) and a 10% error rate. Error again is equated with the percent that could not otherwise be sorted into the specified alloy groups and therefor remains comingled (MLC). Then we increased the error all the way up to 100% and did this for short ton values of 50, 100, 150, 200, 250, 300, 350, and 400. This will give us an idea of how accurate the equipment needs to be and at what volumes can the machine still be profitable. For these models, the amount of hours worked by labor remains at 220 hours, for even if the equipment was not processing high volumes they would still be expected to work. What was then observed was the difference between the profit that would be made by hand sorting without the equipment (Scenario A) and subtracted it from the profit that came as a result of changing these variables to Scenario D. Additionally, an 100 % error for the Steinert can symbolize that the machine isn't working properly and be otherwise interpreted "downtime." This would mean that the yard must revert back to hand-sorting, only having a processing speed of 350 tons/mo, selling a comingled package that now can't be sorted for a lesser price, all while still having the cost to own the equipment and have it repaired. This amount will only be an indicator of what a fraction of the cost would be to consider downtimes, but an indicator that can at the very least express how quickly costs add up when high dollar equipment is down.

Another aspect that needs to be included, are the results of what would happen if the weight of different feeds coming in shifted. For instance, typically >50% of the material in this type of MLC package would be divided between 5052, 6061, 6063, but we need to see how much impact on the profit there would be if this balance changed and lower value 5xxx or 6xxx had a higher volume. To do this, we created a random distribution function and ran it 20 times to find the range in the total profit and price/lb as an additional evaluation of risk.

Technology assessment variables and formulas

Sorting Method Information

Each assessment must begin with identifying the method being evaluated, details of why it is being considered (benefits of method), specifics of the material in question, and the sorting rate/capacity (speed to volume ratio). Table 4.4A exhibits how this looks for the method of sorting by hand and remaining comingled (Scenario A) and Table 4.4B for the Steinert, high-capacity equipment sorting out 5xxx and 6xxx aluminum alloys (Scenario D).

Sorting Method Details (Scenario A)				
Equipment Manufacture & Model (or Method of Sort)	Comingled, Hand Sort			
What does it offer (specifications, size tolerance, etc.)	Minimal Equipment Costs, Minimal Knowledge, High Speed Hand Sorting			
What material are you evaluating its efficacy on	Aluminum MLC ISRI Spec: New, clean, uncoated and unpainted low copper aluminum scrap of two or more alloys with a minimum thickness of 0.015" and to be free of 2xxx and 7xxx series, hair wire, wire screen, punchings less 1/2" diameter, dirt, and other non-metallic items. Grease and oil not to total more than 1% Variations to this specification should be agreed upon prior to shipment between buyer and seller.			
What package are you trying to improve	MLC (Mixed Low Copper Aluminum Clippings and Solids)			
What commodities do you intend to sort	Nonmetallics from MLC			
Scenario	Dump, pick up throw in a hopper, forklift comes over when hopper is full, dumps in roll-off, and returns hopper. 2 hoppers there so no lag time in sorting			
Capacity (per person)	P_h	lbs/hr	$P_h/2000$	tons/hr

Table 4.4A Detailed aspects of Scenario A, goal being a clean MLC package free of contamination.

Sorting Method Details (Scenario D)	
Equipment Manufacture & Model	Steinert LSS | LIBS
What does it offer (specifications, size tolerance, etc.)	Sort Al by alloy type including 5xxx from 6xxx
What material are you evaluating its efficacy on	Aluminum alloys
What package are you trying to improve	MLC
What commodities do you intend to sort	5xxx, 6xxx
Processing Capacity (per person)	4000

Table 4.4B Detailed aspects of Scenario D, goal being an alloy specific sort pulled from MLC packages.

Variables and Descriptions: Receiving and Productivity

The categories, their breakdowns, and corresponding formulas are detailed and described for receiving and productivity in the table below.

Variable	Description	Assigned Value	Formula
S_1	Number of supervisor(s) /Inspector(s) assigned to handling material		
L_1	Number of laborer(s) assigned to handling material		
p_1	The number of pieces sorted per min		
p_2	How many pieces equate to 1 pound		
R	Rate in pounds per minute		p_1 / p_2
L_m	Maximum pounds per person per shift		$R * 60 * H_s$
V_1	The volume the yard is contracted to purchase, expected processing volume per pound		
V_2	Pounds Received less 1% contamination		$V_1*0.99$
P_h	Pounds per hour (capacity per person)		$R* 60$
H_{V1}	Hours required for processing		$HV_1 = V_1/P_h < H_A * \text{Sum}(L_1, S_1)$
L_h	Hours required for processing (per person)		$HV_1/\text{Sum}(L_1, S_1)$
H_s	Hours available per shift	10	
N_s	# of shifts per month	22	
H_A	# of available hours for processing (hrs)	220	$H_s \times N_s$
M_m	Max Capacity per month (includes all laborers): The "processing capacity" in lbs/mo, it is the total amount of volume that can be handled in a month based on shift hours, # of hours in a shift, and total number of people physically assigned to process that material (includes all laborers)	Max $V_1 = M_m$	$\text{Sum}(S_1, L_1) * L_m * N_s$
E_e	New Equipment Percent Error / Comingled: The equipment error, in this model equipment error represents the amount of material that is too difficult to identify (or process) and therefor remains comingled	10%	

Table 4.5 Receiving and productivity variables, details, assigned values, and the associated formulas

Variables, Descriptions, and Formulas: Additional Costs

Freight and Overhead

The freight as described earlier is already included in the price but when a truck shipment is not fully loaded, the price of freight ends up increasing when calculating in the form of dollars per pound shipped. Thus, in the "Formula" section of Table 4.6, the total amount shipped is shown equal to how many additional cents per pound you must subtract from the profit margin. The red box signifies the **total costs** (per lb) calculated in this category that will be subtracted from the total profit margin.

Variable	Description	Assigned Value	Formula
F_1	Freight is included but this variable is still part of the model so if needed, you can change how freight is incorporated. This model has the freight included in the price by pricing material purchased with a delivered quote to the customer and when sold, a price picked up from the yard from the buyer		
F_2	Additional Freight Charges: Underweight penalty ($/lb)	$0.01/lb.	5-10K lbs = $0.04/lb., 10-20K lbs = $0.03/lb., 30-40K lbs = $0.01/lb.
U	Overhead (rent, utilities, insurance)	$0.01/lb.	
$C3_p$	Total Indirect and Additional Costs (per lb)		Sum (F_1, F_2, U)

Table 4.6 Indirect and additional cost information and variables as pertains to freight and overhead.

Additional equipment

Yards require additional equipment simply to be able to operate and move material around the yard. This section is to account for any equipment that must be bought to operate potentially new equipment purchases and/or the allocation of time being used by this equipment for a particular sorting method. The red box signifies the formula needed to get these additional costs into price per pound in order to determine **total costs** (per lb) calculated in this category that will be subtracted from the total profit margin.

Variable	Description	Assigned Value	Formula
A_{c1}, A_{D1}	Additional Equipment Cost 1, Additional Equipment Depreciation Cost 1	A_{c1} = $45,000 Forklift	$A_{c1}/7/12 = A_{D1}$ *Straight line depreciation
Ac2, AD2	Additional Equipment Cost 2, Additional Equipment Depreciation Cost 2	-	$A_{D1}/7/12 = A_{D1}$ *Straight line depreciation
T_{c2}, T_{D2}	Total costs, Total Depreciation Costs per month	$T_{c2} = A_{c1} + A_{c2}$	T_{D2} = Sum (A_{D1}, A_{D2})
$C2_P = D2_P$	Total Additional Equipment Costs/lb		$D2_P = TD_2/V_1$

Table 4.7 Additional equipment cost information, details, and variables

Variables, Descriptions, and Formulas: Costs of Labor

The model gives you the ability to consider any number of laborers you want to assign to a method and allows you to assign them different costs (or pay amounts), this is detailed in Table 4.8 below. New labor will be less expensive than a trained instructor (salary), or experienced equipment operators. Variables L and S, allow you to distinguish the workers by their pay; assigned values for average pay were acquired from the expert interviews discussed in the introduction. They were averaged to account for the price fluctuations that occur across the United States. The total costs of labor (T_{c1}) is divided by the total volume of material they were had to process, the red box gives the price per pound cost of labor to be subtracted from the total profit margin.

Variable	Description	Assigned Value	Formula
L_1 L_h L_c L_A	Laborer(s)/HH Operator	$L_1 = 2$	$L_c = L_1 * L_h * L_A$
	Laborer(s) hours required for processing	L_h = processing hrs	
	Laborer(s) Cost	L_c = $/mo	
	Average Pay	L_A = $ 13.5	
O_1 O_h O_c O_A	Forklift/Skid Steer Operator	$O_1 = 1$	$O_c = O_1 * O_h * O_A$
	Forklift(s) hours required for processing	O_h = processing hrs	
	Forklift operator(s) Cost	O_c = $/mo	
	Average Pay	O_A = $ 15	
O_2 O_{h2} O_{c2} O_{A2}	Front Loader Operator	$O_2 = 0$	$O_c = O_2 * O_{h2} * O_{A2}$
	Front Loader Operator (s) hrs required for processing	O_{h2} = processing hrs	
	Front Loader (s) Cost	O_{c2} = $/mo	
	Average Pay	O_{A2} = $ 19	
S_1 S_h S_c S_A	Laborer(s)/HH Operator	$S_1 = 0$	$L_c = L_1 * L_h * L_A$
	Laborer(s) Hours required for processing	S_h = processing hrs	
	Laborer(s) Cost	S_c = $/mo	
	Average Pay	S_A = $ 25.00	
T_{c1}	Total costs		T_{c1} = SUM (O_{c1}, O_{c2}, L_c, S_c)
$C1_P$	Total Labor Costs ($/lb/mo)		T_{c1}/V_1

Table 4.8 Labor cost information, details, and variables

Variables, Descriptions, and Formulas: Purchases, Sales, and Profits

Receiving

When you evaluate "Receiving," you are looking at the costs of purchasing the material. For this assessment we are looking at purchasing MLC packages and transforming them into a product with reduced contamination and/or sorting out a specific alloy. In Table 4.9, the variables, and formulas for purchasing the MLC are defined. The "adjusted MLC" purchase price is the actual price per pound you paid if you consider the amount of weight removed as contamination while also adding in the cost to landfill (tipping fee) and then re-evaluate with the total costs you paid to the customer divided by the actual volume of what was in fact MLC (and not contamination). Table 4.10 are the variables and formulas used for any case where you are selling the product out as the same product in, but it has deducted the weight lost due to contamination removal. For a detailed look at the models for Scenarios A-E, when applying the values at maximum capacity processing speeds, see Appendix A.

Variable	Description	Formula	
		$/lb.	Total Purchase Cost(s)
X_{1P}	MLC Purchase Price (Del)		$X_{1P} * V_1$
$-X_{1P}$	Non-Metallics		$(X_{1P}) * (V_1 * .01)$
B	Tipping fee per lb		$B * (V_1 * .01)$
X_{1A}	Adjusted MLC Price	$X_{1a} = ((X_{1P} * V_1) + (B * (V_1 * .01)))/ V_2$	$(X_{1P} * V_1) + (B * (V_1 * .01))$

Table 4.9 Costs to receive MLC

	Variable	Description	Formula
MLC	X_{1S}	MLC Sale Price (Picked up)	
	X_{1r}	Expected % Volume (ratio)	
	V_{X1}	Total lbs	$X_{1r} * V_2 = V_{X1}$
	X_{1G}	$/mo	$X_{1S} * V_{X1} = X_{1G}$
	W_{X1}	Weighted Value/lb	$W_{X1} = X_{1G}/ V_2$

Table 4.10 Calculations for determining the amount earned from selling MLC

Summary and checks

The end result of the technoeconomic assessments after factoring in cost and profit possibilities are summarized at the end of each model in the categories defined in Table 4.10. The checks are other formulas that when calculating different variables or variables in a different way should equal the same as the values in the summary. The checks for a particular category are shown in the same row in Table 4.10 however, in Appendix A, they are differentiated by the box border colors.

Summary		Checks	
Description	Formula	Description	Formula
Gross: Comingled	See Appendix A	-	-
Costs for operating Volume received (V_1)	See Appendix A	Costs = Actual Purchase Price - Adjusted Purchase Price	See Appendix A
Total Costs as applied to actual lbs sold (including purchase cost)	$X_{1r} * V_2 = V_{X1}$	-	-
Profit/lb	$X_{1S} * V_{X1} = X_{1G}$	-	-
Profit less costs per pound	$W_{X1} = X_{1G}/ V_2$	Sale Price - [actual purchase price]	$X_{1r} * V_2 = V_{X1}$
(A) Profit per lb * actual shipped weight	$X_{1S} * V_{X1} = X_{1G}$	Net = Gross – Costs	(A)-(B)
(B) Operating costs for volume received * actual shipped weight	$W_{X1} = X_{1G}/ V_2$	Sale Price - [Profit less costs per lb]	See Appendix A

Table 4.11 Cost/profit calculations, and additional calculations that help verify all inputs were included in the end results.

4.3 Results and Discussion

Historical market and commodity price comparisons

To understand how fickle the aluminum market is and can be, not only did we collect data to show a decade timespan of historical market and commodity pricing over a 10-year period (Fig. 4.1), but we also obtained data to show how it varies from other nonferrous materials like copper (Fig. 4.2). The graphs below help depict how significant price gaps can be between different metals and their relationship to the market. When it comes to copper, scrap prices here generally stay at a discount to the COMEX, whereas aluminum secondary prices can oscillate above or below. Furthermore, copper commodity pricing is primarily based on the percent copper that can be recovered. Generally, between bare bright copper (BB) (highest purity), #1 copper, and #2 copper, they all maintain this consecutive order beneath the primary market. Other key aspects to consider here are not only the differences in the intrinsic values but also, the differences in their corresponding densities. Copper is worth 3-4 times as much as aluminum however, this means your capital costs are going to be high. This is extremely important to consider as payment terms have transitioned to being more immediate where in the past you could have 30-day contracts. In other words, you have to be able to give a substantial amount of money in advance before you yourself are getting paid on the material. Aluminum is less in value, which means a lower up front cost to purchase, but you have to put more time into processing the material to equate to the weight of copper; ergo a lot more material to equal the same weight. On the other side of the spectrum there's ferrous scrap, which is 10 times less the price of Al but it's easy to process a lot and quickly. The evaluation of scrap metal costs and benefits demands understanding these types of trade-offs when purchasing, processing, and selling different types of material.

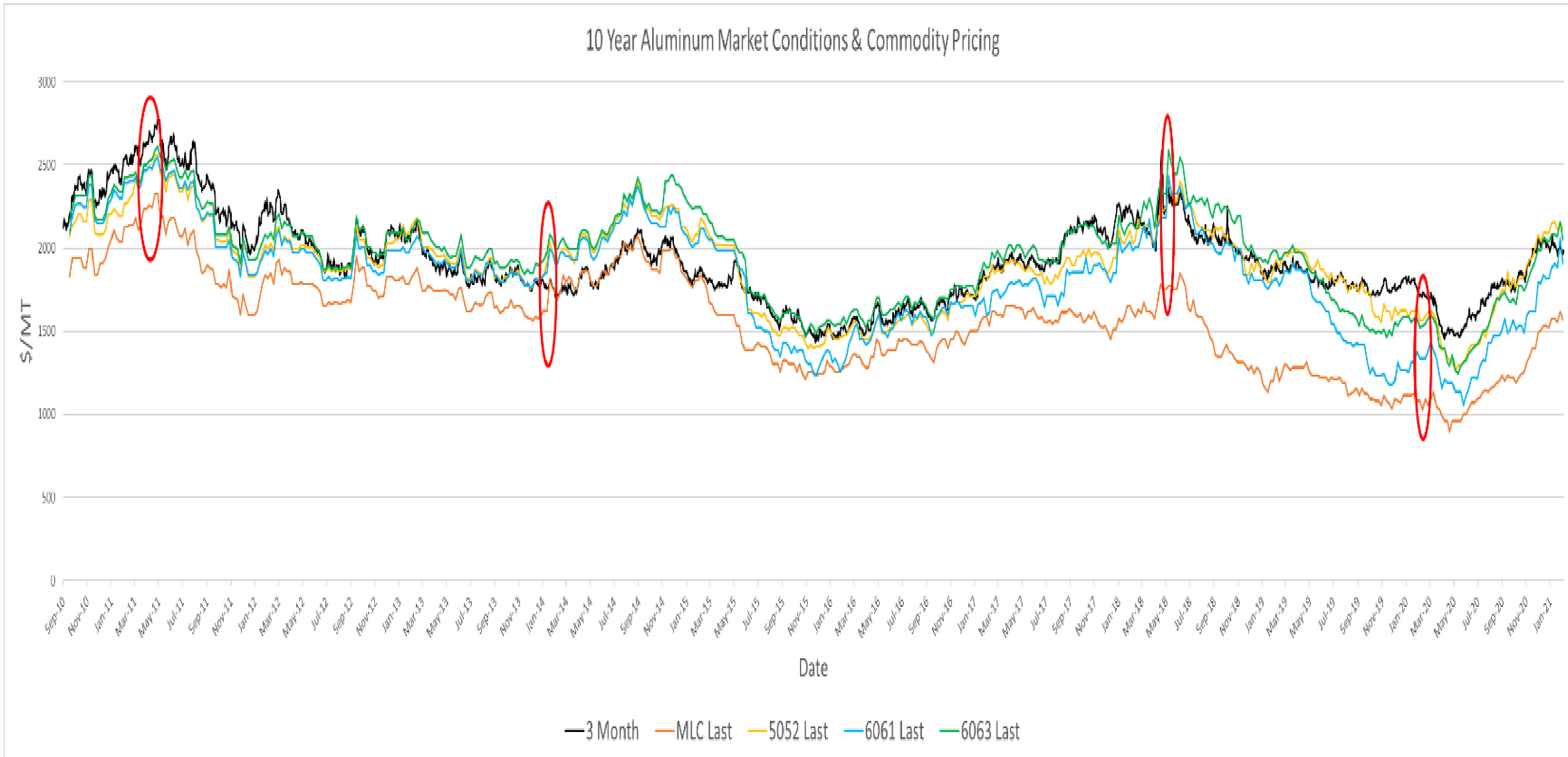


Figure 4.1 Permissions gained from Argus to obtain market data and commodity prices for academic purposes only. LME Aluminum commodities and market conditions in dollars per metric ton. Red circles indicate the markets we chose to evaluate and compare in our model – values are specified in the table below.

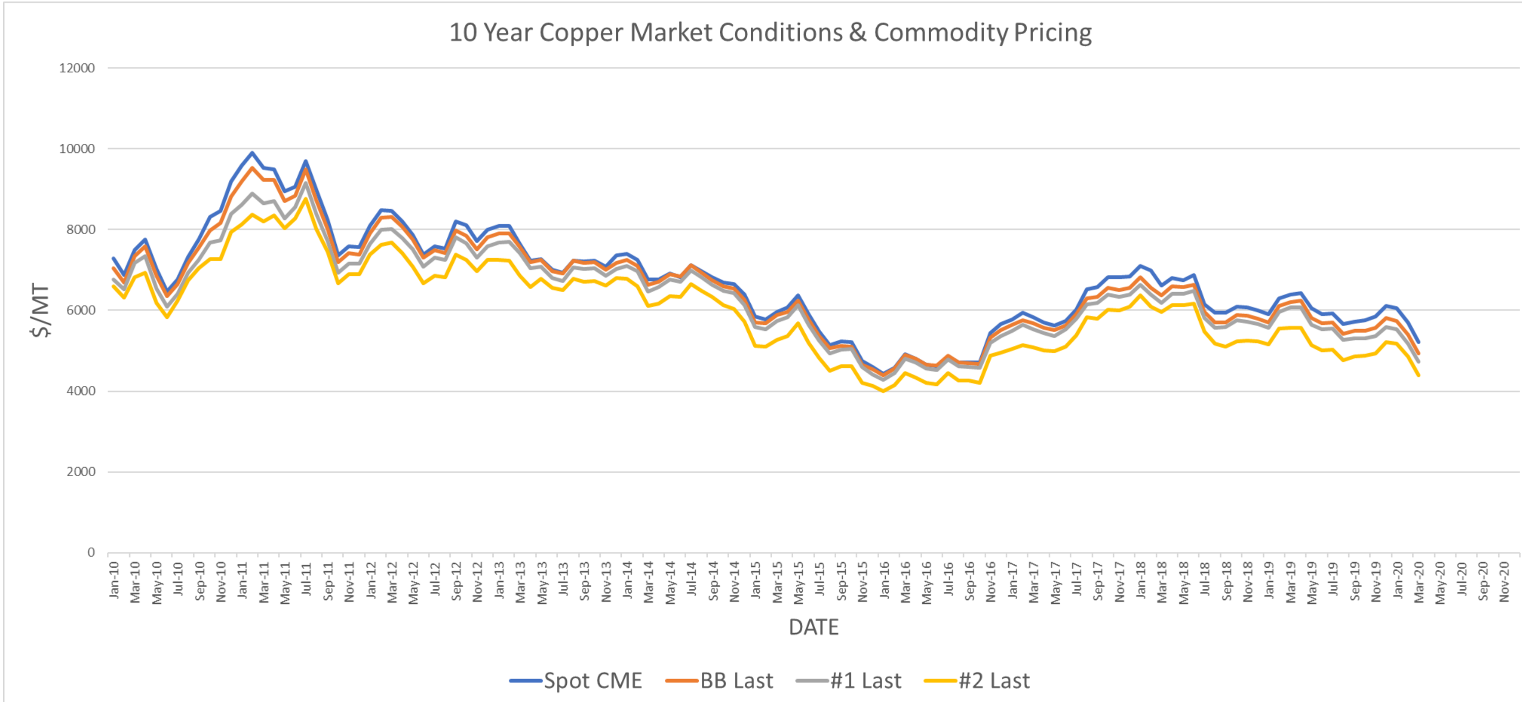


Figure 4.2 Permissions gained from Argus to obtain market data and commodity prices for academic specified purposes only. COMEX Copper commodities and market conditions in dollars per metric ton.

The markets and the associated commodity prices that were evaluated in our model can be found in Table 4.12. The Feb20_0.776 was the first market we explored, for it was the current condition of the market when we started looking to quantify these technologies for aluminum. Figure 4.2 was then used to find markets with different relationships between commodities and their placement above or below the LME (as indicated by the red circles). Additional considerations were made by observing the different spreads between alloys and also the spreads between the alloys and MLC.

			Scrap Commodity Sale Prices					
Reference #	Al Markets	3 MO Avg LME	Misc 5xxx	5052	Misc 6xxx	6061	6063	MLC
1	Feb 2020	0.776	0.615	0.718	0.640	0.610	0.700	0.483
2	May 2018	1.04	0.948	1.048	1.082	1.052	1.118	0.799
3	Feb 2014	0.788	0.795	0.895	0.915	0.885	0.920	0.801
4	Apr 2011	1.218	1.039	1.139	1.165	1.135	1.158	1.034

Table 4.12 Reference numbers for corresponding aluminum markets, and associated commodity prices for those markets.

Quantitative comparisons of alternative techniques

Scenario A-E were compared in the Feb20 3mo LME market (Market 1). We can see that with low volume, high sorting accuracy, and equipment costs less that 100K, there is opportunity for significant improvements in profit. Whereas not upgrading your material and selling it comingled is profitable, but it is the least profitable. Figure 4.3 and 4.4 of all the technologies graphed side-by-side is extremely significant because regardless of being able to predict this outcome, there has not been any work that was able to quantify the value of these tools/technologies. This is likely due to what is involved in and what must be known to capture all these parameters. It is not necessarily that results are unforeseen, for instance, we know using handheld analyzers can considerably reduce sorting speeds but being able to quantify the trade-offs of an improved bottom line is novel.

Nonferrous Scenarios (A-D)

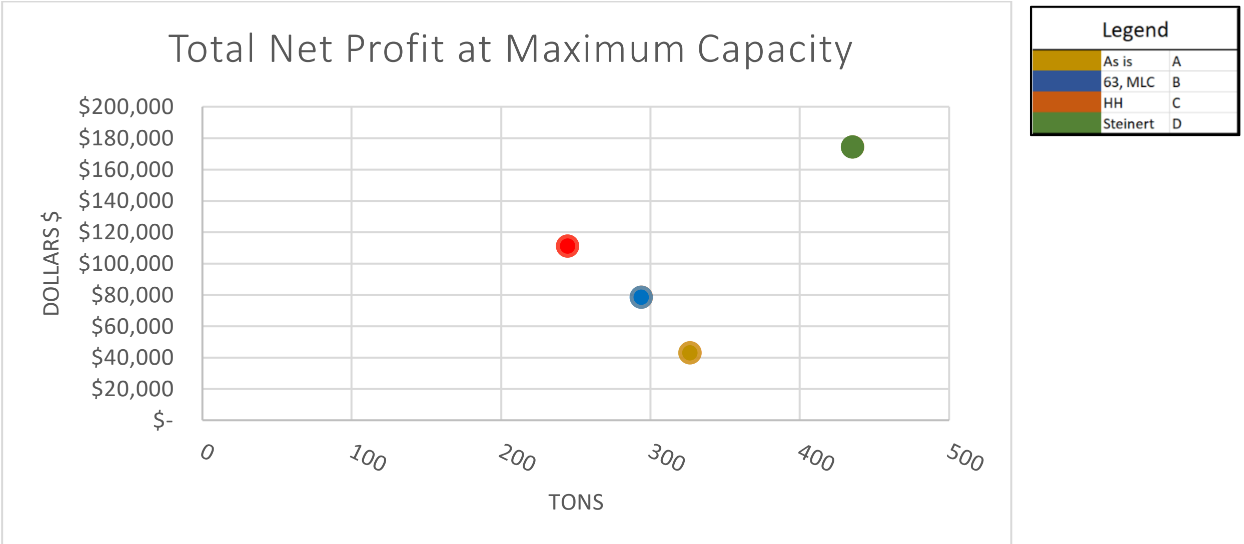


Figure 4.3A Scenario comparisons of the net profit (gross profit less costs) that can be made at maximum capacity in Market 1. The graph above demonstrates the differences in the capacity to operate and prepare a product quickly for simple vs. more detailed sorting.

Nonferrous Scenarios (A-D)

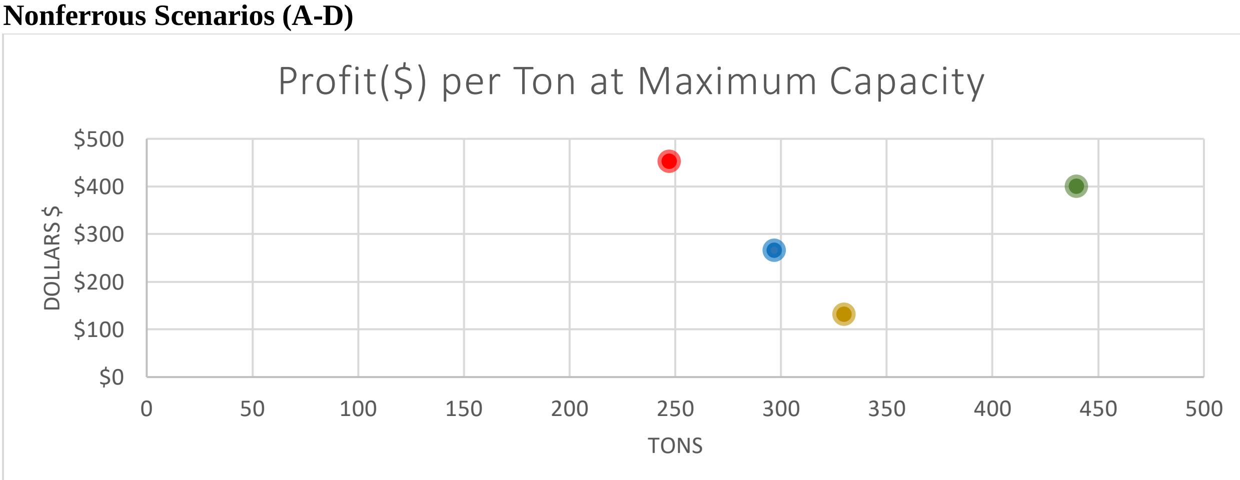


Figure 4.3B Scenario comparisons of the net profit per ton (gross profit less costs) processed at their fastest speeds for Market 1. Handhelds, although the slowest method, show that if the accuracy rate of the sorting ability is high, profit per unit is higher. However, the trade-off is that less total material can be processed in the time allotted, leading to a capped profit.

_Nonferrous Scenarios (A-D) Compared with Ferrous High-Capacity Shredder (Scenario E)**

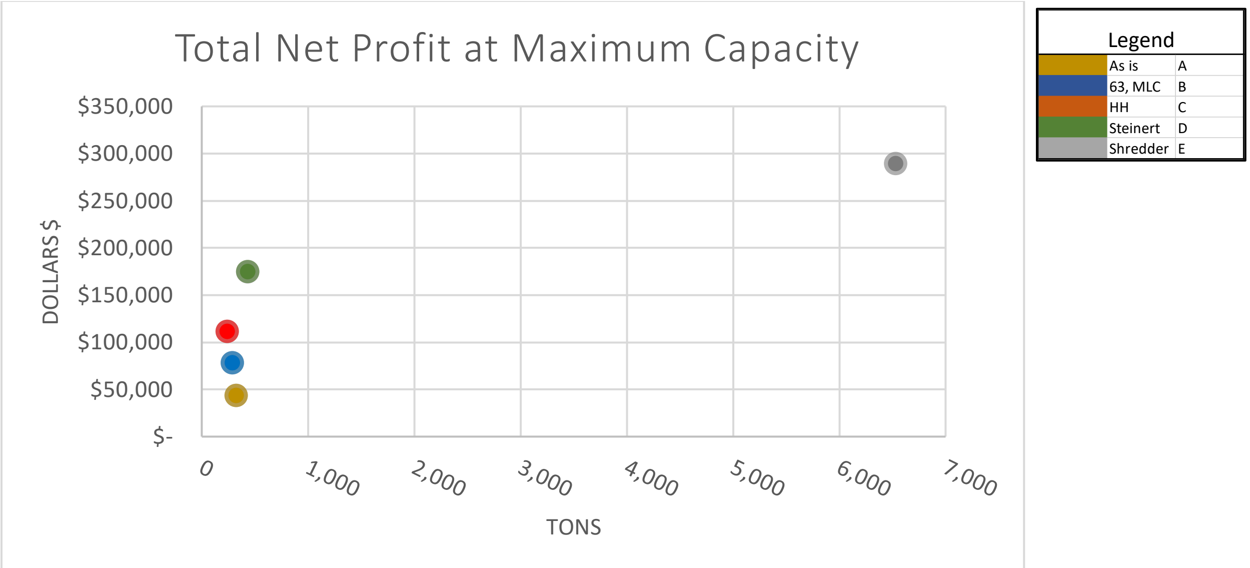


Figure 4.4A Scenario comparisons of the net profit (gross profit less costs) that can be made at maximum capacity in Market 1. The graph above demonstrates the differences in the capacity to operate and prepare a product quickly for ferrous vs. non-ferrous materials. Speeds are nearly 15 times as fast however, the profit is only twice that of the highest speed non-ferrous sorting.

Nonferrous Scenarios (A-D) Compared with Ferrous High-Capacity Shredder (Scenario E)

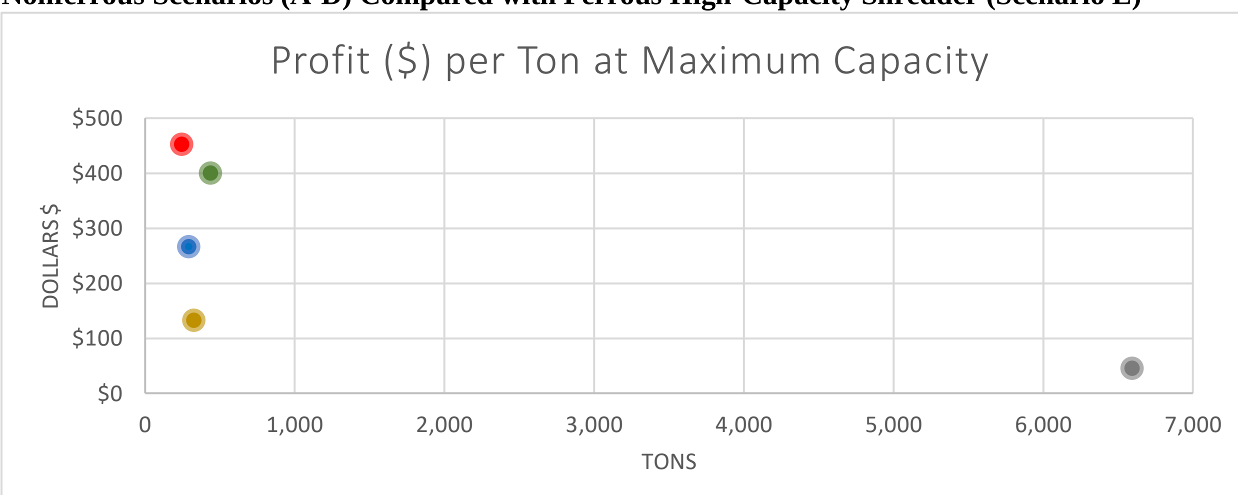


Figure 4.4B Scenario comparisons of the net profit per ton (gross profit less costs) processed at their fastest speeds for Market 1. The graph above shows how miniscule the price per unit of ferrous is when compared to nonferrous alloys, but you visibly see the distance between the volumes of materials and how its low unit price is offset by the incredible amount of volume handled.

Return on investment (ROI)

Table 4.13 gives the likely return on investment outcomes at a low and high volume in Market 1 for the handheld analyzers, the Steinert LIBS, and a high-capacity shredder. Also included, is a backward calculation of how much material would be required and the expected profit per month necessary to pay off the equipment in a specified time. For instance, with costs under six figures (two handheld analyzers), the goal would be to have the equipment pay for itself in 1 year. The amount of profit that would need to be made per month is a simple and quick calculation. Then using the model, found in appendix A, you can change the volume processed to determine how many pounds you would need to receive to equate to the correlated profit per month needed to pay off the equipment, while also including all the variables specific to your operation; in this model, the variables described in Tables 4.4A through 4.11. The "low-end" capacity is an indicator of how much processing per month is required before you are losing money. Thus, if there are downtimes, or months where some suppliers aren't generating and shipping enough material, this number advises the company the least amount possible that must be received and sold before the costs outweigh the benefits. Because of how the model is designed, it also indicates how much material can remain unsorted (comingled), the details of this can be seen in appendix A models (not from the ROI table). Lastly, the maximum capacity includes the best case scenario of all the variables and the equipment operating at the fastest speeds possible (given the various constraints). Without any problems (which in itself, unlikely), the pay-off time, for all the equipment, could be under a year.

		Handheld Analyzers			
		Total Equip Costs	Profit /mo	Months	Years
ROI	Max capacity (495K lbs/mo)	$ 60,000	$105,700	0.6	0.0
	Low-end capacity (100k lbs/mo)	$ 60,000	$ 20,900	2.9	0.2
	Goal: 1 year @26k lbs/mo	$ 60,000	$ 5,000	12.0	1.0
		Steinert			
		Total Equip Costs	Profit /mo	Months	Years
	Max capacity (880K lbs/mo)	$ 1,795,000	$173,800	10.3	0.9
	Low-end capacity (100k lbs/mo)	$ 1,795,000	$ 1,000	1795.0	149.6
	Goal: 7 year @194k lbs/mo	$ 1,795,000	$ 21,800	82.3	6.9
		High Capacity Shredder			
		Total Equip Costs	Profit /mo	Months	Years
	Max capacity (880K lbs/mo)	$ 2,775,000.00	$288,600	9.6	0.8
	Low-end capacity (100k lbs/mo)	$ 2,775,000.00	$ (36,600)	-75.8	-6.3
	Goal: 7 year @3million lbs/mo	$ 2,775,000.00	$ 35,300	78.6	6.6

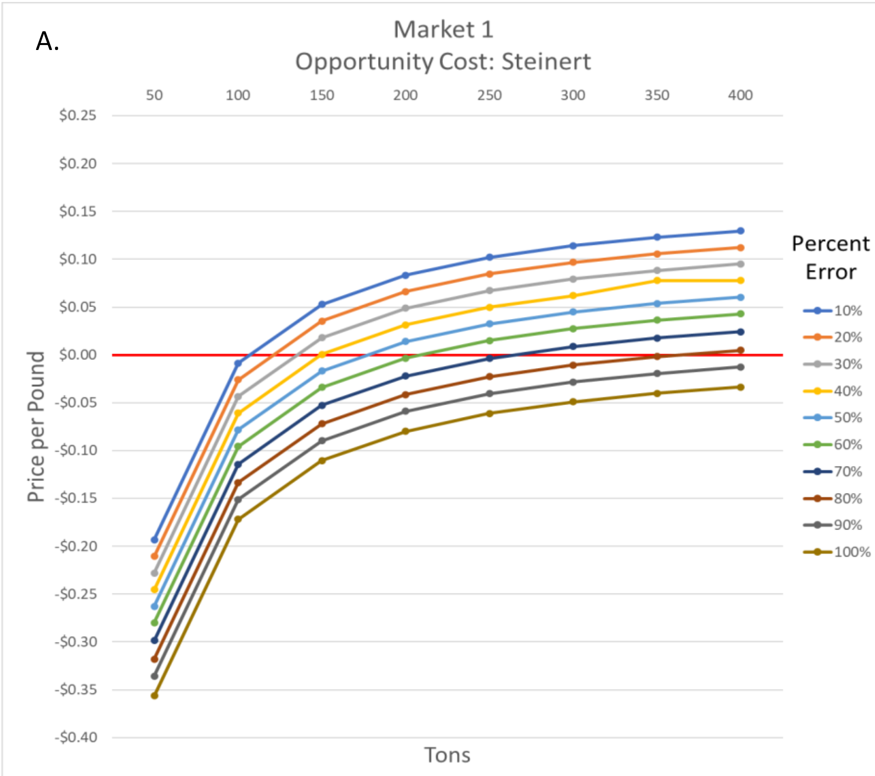
Table 4.13 ROI summary for Steinert, handheld analyzers, and a high-capacity ferrous shredder. *Shredder must process >2million lbs./mo (1,000 tons) or will incur losses.

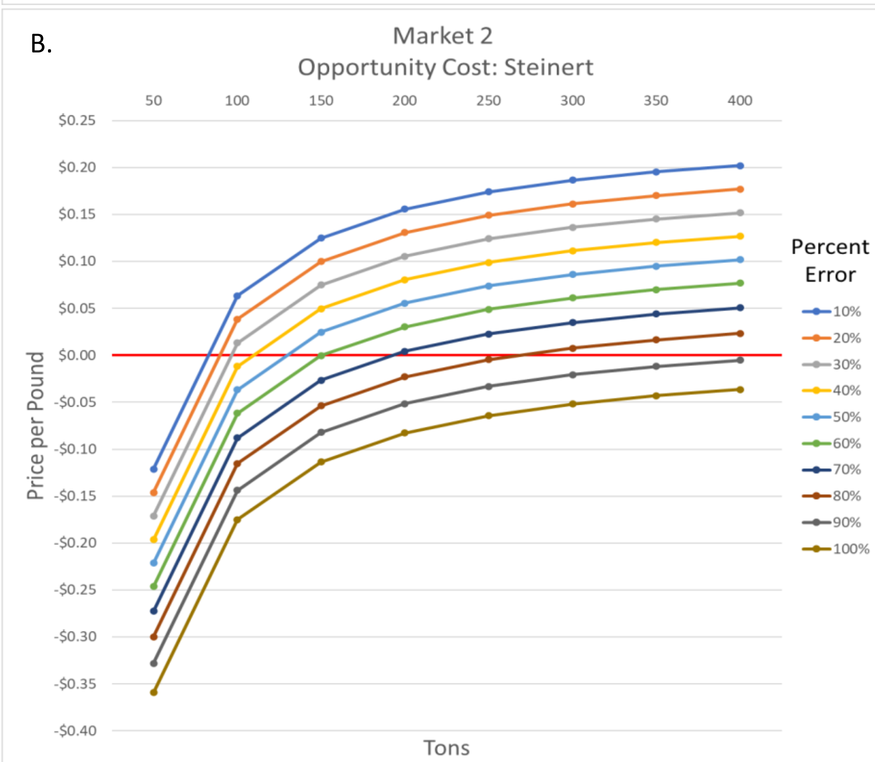
Opportunity cost

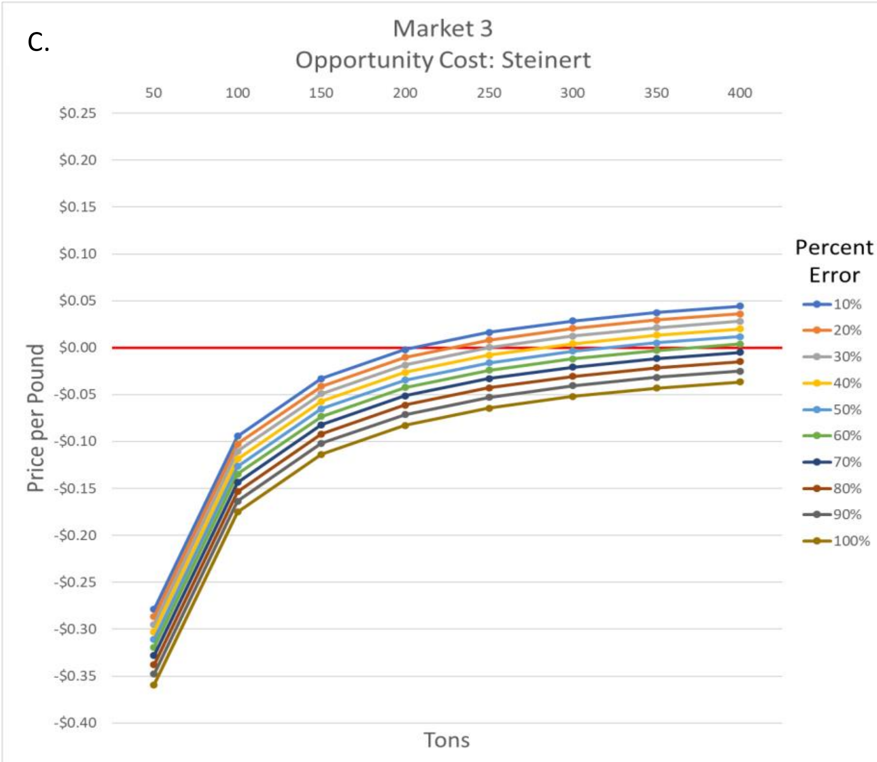
In the graphs 4.5A-D below, the difference between the profit to be made from hand sorting but leaving comingled (Scenario A) and the profit to be made from using the Steinert to perform an alloy specific sort, was looked at in 4 different markets, with the associated commodity prices of those markets. Graphs display the fluctuations in tonnage from low volume to high for tonnages of 50 - 400 tons at percent errors ranging from 10% to 100% for the Steinert. Again, percent error means the amount of material that went through the equipment but was unable to be identified and sorted into the unique alloy groups that have been specified, and therefore, must be sold as the comingled MLC package that it was bought in as.

There are several things this evaluation allows you to extrapolate. First, we consider the equipment is operating and being used for the maximum number of processing hours there are in a month, 220hrs. The most that then can be processed in a month with the Steinert at a speed of 4000 lbs/min, is 880,000 lbs, the graphs are designed to jump by even increments of 50 tons, thus, what's graphed only includes up 800,000 lbs (400 tons). These graphs show that with costs of equipment, labor and overhead, the equipment can have a relatively high level of error in markets 1 & 2 (Fig 4.5 A&B), but generally speaking if we were to consider the riskier markets, 3 & 4 (Fig. 4.5 C&D), then an error no lower than 40% would be profitable if you are moving material at max volume capacity. For these models, the number of hours worked by labor remains at 220 hours, for even if the equipment was not processing high volumes employees would still be expected to work (and then speeds are reduced to how fast the material could be sorted by hand).

These graphs also give you a possible way to view the impact of downtimes. You could assume 100% error and look at tonnages of 300 tons and less, this would be the equivalent of selling the material comingled at a volume that can be reasonably processed by hand, but you are still factoring in the costs of the equipment and the equipment needed to run the equipment. Additionally, you would need to consider increased labor times, for processing by hand means only being able to move 3,000lbs an hour rather than 4,000lbs an hour, and again capping how much you can process in a month. However, it is important to note that with the equipment down, you might not be able to process that material at all. The specific alloys sorted out might be promised through contracts, meaning preference by the consumer might be dealing with a delay of shipment over not getting the material at all. Therefore you would have to keep paying for the material as it comes in, while not being able to sell out as a different package, and waiting until the machine is fixed.


A.
Market 1
Opportunity Cost: Steinert
50
100
150
200
250
300
350
400
$0.25
$0.20
$0.15
$0.10
$0.05
$0.00
-$0.05
-$0.10
-$0.15
-$0.20
-$0.25
-$0.30
-$0.35
-$0.40
Price per Pound
Tons
Percent Error
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


B.
Market 2
Opportunity Cost: Steinert
50
100
150
200
250
300
350
400
$0.25
$0.20
$0.15
$0.10
$0.05
$0.00
-$0.05
-$0.10
-$0.15
-$0.20
-$0.25
-$0.30
-$0.35
-$0.40
Price per Pound
Tons
Percent Error
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%



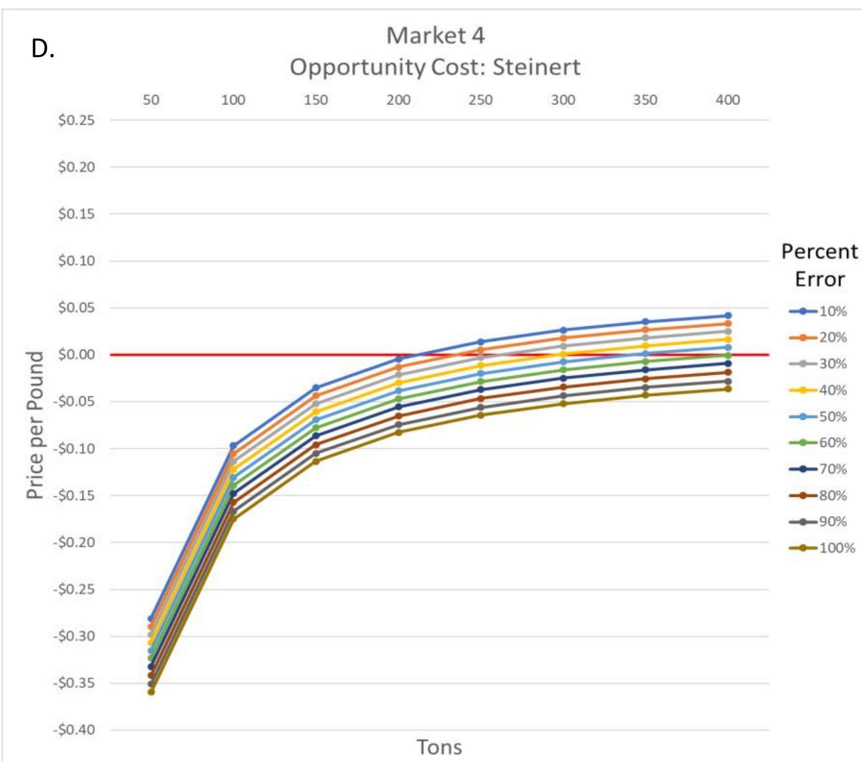


Figure 4.5A-D Opportunity costs of market conditions 1-4 (Table 4.1)

Randomized Volume Distribution

Because it is unlikely for feed distributions to always be exactly the same, it is important to get an idea of by how much they could fluctuate and how that would then impact the profit. We looked at changing the distribution for all alloys in Market 1 at the highest processing capacity for the Steinert (2 tons/hr for 220 hrs.). The results show an overall range of $0.03/lb. This may not seem like a lot at first glance, but what always must be kept in mind is that pennies at high tonnages are still liken to large losses. In the case of 880,000lbs, the costs from 1% contamination and tipping fees, added to a $0.03/lb loss equates to $29,480.

Random Vol Distribution #	Net profit ($/lb)	Al - Misc 5xxx	Al - 5052	Al - Misc 6xxx	Al - 6061	Al - 6063	% Error (Comingled MLC)	Net Profit Range ($/lb)
Initial	$ 0.200	11%	17%	10%	22%	30%	10%	$ 0.03
1	$ 0.208	10%	15%	0%	21%	45%	10%	
2	$ 0.188	33%	4%	22%	4%	28%	10%	
3	$ 0.187	16%	4%	33%	13%	23%	10%	
4	$ 0.188	21%	17%	27%	14%	11%	10%	
5	$ 0.180	30%	3%	0%	30%	27%	10%	
6	$ 0.179	23%	3%	15%	27%	21%	10%	
7	$ 0.200	20%	27%	14%	11%	17%	10%	
8	$ 0.186	19%	24%	18%	26%	4%	10%	
9	$ 0.195	6%	28%	28%	22%	5%	10%	
10	$ 0.210	2%	20%	29%	7%	32%	10%	
11	$ 0.192	17%	17%	13%	22%	21%	10%	
12	$ 0.213	4%	28%	14%	13%	30%	10%	
13	$ 0.189	30%	8%	2%	19%	30%	10%	
14	$ 0.187	17%	8%	1%	35%	29%	10%	
15	$ 0.194	12%	6%	18%	20%	35%	10%	
16	$ 0.207	9%	31%	2%	24%	24%	10%	
17	$ 0.207	10%	23%	31%	1%	25%	10%	
18	$ 0.190	15%	28%	3%	35%	8%	10%	
19	$ 0.181	5%	20%	12%	47%	5%	10%	
20	$ 0.197	10%	22%	15%	23%	20%	10%	

Table 4.14 The random volume distribution trial number is specified in the first column, the net profit (total profit minus costs) can be found in the 2nd column, followed by the feed distributions of the different alloys. Percent error is kept constant, and the resulting range can be found in the red boxed cell.

4.4 Conclusions

In theory, it makes sense to presume that sorting materials into individual alloy groups when you can get premium pricing for doing such is the way recycling facilities would then naturally operate. However, labor costs and the time to process the material can devour margins, meaning the price difference between the purchase and sales price should figure at least a $0.10/lb margin to protect themselves from unforeseen costs that can arise and changes in market conditions. This approach should be applied to all levels of processing, especially bare minimum sorting represented by Scenario A, as contamination is unpredictable and costly. Scenarios B-E allow opportunity to increase your profit margin by sorting out an alloy of greater value, or by drastically increasing the volume per hour, or both. The section on ROI (Table 4.13) shows the minimum amount that can be processed before losses occur; however, it demonstrates that this is not a sustainable way of operating, for the time it takes to pay off the costs of the equipment at these volumes becomes unacceptable, or not possible.

Modeling the scenarios under different market conditions revealed that the key condition to maximizing the investment in equipment is neither high commodity prices, nor is it increased intrinsic value of the alloy. At lower commodity prices, not only do you have to spend a lesser amount when buying large sums up front, but if market conditions proceed to widen the margin between the worth of a comingled commodity and the alloys it can be sorted into it, then there is a lot of room for economic opportunity at a lower risk. The safest markets were when the LME was at $0.776/lb (Market 1: February 2020) and at $1.04/lb (Market 2: May 2018) and that is because the marginal gaps between MLC and the other alloys were all greater than $0.12/lb, some reaching as high as $0.32/lb. Whereas in markets when the LME was at $0.788/lb (Market 3: February 2014) and 1.218/lb (Market 4: April 2011) some of the alloys had less than a $0.10 gap between them and MLC, and there were instances of alloys being approximately the same price or even slightly under. This establishes that the relationship between the product you are purchasing and the product you are processing to sell, is more significant than where the actual LME 3mo market is; because premiums are paid regardless of where the market lies if demand for a specific secondary scrap alloy is high. These results indicate that if increased demand for secondary materials continues to rise in the future, then the benefits would outweigh the costs of owning advanced technology/equipment; making their implementation economical to recyclers on a larger scale and increasing the potential to produce cleaner, more pure material streams.

Another key takeaway is that a strong customer base that guarantees a consistent feed supply is crucial to being able to own and operate expensive equipment for sorting and separation. Shredders, although millions of dollars to purchase, can process an inconceivable volume of material per hour. This amount proved to be magnitudes higher than any other sorting or processing method, necessitating it be graphed separately when comparing net profit to capacity (Figure 4.3 & 4.4). However, even with shredder volume capabilities being extraordinary, in this case 15 times the amount of volume the Steinert can process, it still only produces roughly twice the profit. Whereas the sorting methods focused on nonferrous identification, can lead to profits that increase exponentially by comparison. Furthermore, prioritizing high volume at low margins can be extremely high risk, for shredder owners often experience downtimes which directly correlate to major losses.

It is important to remember that regardless of how many variables and parameters are evaluated, there will always be unknowns or unforeseen changes. Although thorough, these are narrowed views of the scrap yard and its materials. Taking a step back, there are several things that aren't incorporated, like the availability to make larger margins from peddler scrap when buying in smaller volumes at a time, or opportunities for some of the MLC to be bought in at a lower price from specific customers because the yard is paying them more through some other commodity. These are only a couple examples of the several other potential losses and gains that can occur at nonferrous and ferrous operations that are not accounted for in these assessments. However, the models are designed so that the scope can be extended, and they can be modified and applied to very specific cases.

This technoeconomic assessment showed that even a high amount of comingled material can be profitable at high volumes but on the flipside, it also conclusively proved that there is potential to have all the ideal outcomes: high volume, profit, *and* cleaner, more pure scrap streams. There still are and may always be materials that slip through and become comingled, making contamination an ongoing concern. Although, we are not without options to reduce these outcomes from other angles. Implementing more concepts like extended producer responsibility and contemplating how to design products for recycling, puts accountability on both ends of the supply chain, supporting our waste management and recycling industries as opposed to continually adding onto them more weight – figuratively and literally. The more we work to bridge gaps in our understanding of what's possible and educate each other, the greater our ability to drastically improve the outcome of materials having multiple useful life cycles. Just as climate change was inevitable in time, so too is the accumulation of tramp elements, but we have the ability to slow that process as opposed to being the catalyst.

Chapter 5
Conclusions and Recommendations

5.1 Research Implications

Central to achieving sustainable solutions is the application of systems thinking. Effectively applying this type of analysis to design a more environmentally conscious supply chain approach, ultimately retiring our make-take-waste mentality, necessitates we consider everything from product design to treatment of materials that have reached their end of life (EOL). Primary ore extraction is a drain on our land, energy, and resources, and we have the ability to reduce our need for these types of raw materials. Investing in and considering the ways we can improve secondary utilization rates, specifically for ferrous and nonferrous metals as well as looking at the challenges faced by the industry in charge of managing these materials at the EOL, is integral to making large scale, impactful changes. Metals [or scrap] recycling operations, are met with an array of challenges when it comes to identifying, sorting, processing, and preventing contamination, and it is the efficacy of these processes that influence the use of secondary materials over primary. This work looks at the intricacies of these system processes to reveal what must happen to increase, and what can happen to derail materials from re-circulating.

In Chapter 2, the challenges of receiving, identifying, sorting, processing, packaging, and shipping ferrous and nonferrous metals are discussed from the yard's perspective, divulging why, what, and how decisions are made. While detailing how complex, unique, and arduous these processes are, the chapter pinpoints what makes these processes so challenging and how existing literature glosses over such aspects when evaluating technologies and their potential to improve scrap industry processes. Additionally, searching for literature that evaluates inspection, identification, and contamination of different metals typically yields results involving issues that arise at a secondary producer such as a mill or foundry. Research in this area is necessary for establishing mitigation techniques but, identifying what can be done to prevent problems from arising is the goal of the work presented throughout this dissertation. Addressing this gap in literature and finding preventative solutions requires increasing awareness and understanding of what is happening in the yards. This meaning, uncovering detailed information of what influences how materials are processed, the intricacies of inbound inspection, identification, and sorting, and finally, introducing and evaluating the different types of technologies, what said goal of the technology is, and identifying the limitations when applying newly developed technology to this industry and its operational challenges specifically. Chapter 2 informs readers that the majority of yards that exist didn't start their business with the intention of reducing the amount of primary metal used in the production of new goods. Thus, it is unsurprising that when tasked with identifying, sorting, and processing mass amounts of mixed metals into the clean material streams that are desired, they are ill-equipped. Recognizing the enormity of work required to transform materials from the form it is received into the yard to the form that is acceptable to ship is key to discovering technology solutions that can be integrated and widespread.

Chapter 3 breaks down characterization techniques into three categories: integrated, laboratory, and in-situ. The common denominator amongst these different types of technologies is that they all require cleaning or "preparing" the material to perform the most reliable identification testing and subsequent sorting. However, it is this very limitation that prevents most technology from fitting in with the normal flow of operations. Receiving and processing materials must be fast-paced, and with the scrap and scrap condition constantly changing, it is not practical to pre-prep all materials in this way. Moreover, obsolete scrap is the most difficult to sort and identify due to its often weathered, warped, and/or contamination-coated surface, but it is the most prevalent; meaning, technological assistance in this area would have a significant impact on reducing incorrect identification. Experimental data and quantitative analysis were collected by using some of the leading technologies in positive material identification (PMI), XRF and LIBS handheld analyzers. Six different makes and models were evaluated by testing their performance on an assortment of common and often problematic scrap types. As a result, physical evidence could be provided to demonstrate that even with useful, advanced technology, quick on the spot identification testing falls short in addressing the realities of what condition scrap metal is in upon being received and inspected. Alternatively, it does make clear that the ability to reveal the chemistry of a metal/alloy in seconds, with low-cost equipment would be the ideal "staple" tool in the pursuit of producing less-contaminated material streams. There is no previous literature that has addressed the wealth of knowledge that is needed to correctly identify metals through visual inspection and a few standard tools alone. Every metal group requires a different set of knowledge and a different process for handling. Therefore, tools that can reduce training times and eliminate the high level of uncertainty that accompanies accepting a wider range of materials is invaluable to these types of operations.

The technoeconomic assessment performed in Chapter 4 focuses on production, labor, and equipment costs as well as the more difficult to predict costs such as downtimes. Additionally, it emphasizes that there are several costs that fluctuate based on geography such as landfill costs, material rejections, freight, insurance, permits, and various fines. It demonstrates how-quickly profit margins can dwindle especially when processes are inefficient, and the volume of contamination and capital costs are high. By modeling 5 separate scenarios under changing market conditions, the key condition to maximizing the investment in equipment was realized, and it was neither high commodity prices, nor increased intrinsic value of the alloy. At lower commodity pricing, not only do you have to spend less when buying large sums up front, but if the market conditions then widen the size of the margin between the worth of a comingled commodity and the alloys it can be sorted into it, then there is a lot of room for economic opportunity at a lower risk. Additionally, the relationship between the product you are buying in vs. the product you are turning around is more significant than where the actual market lies (in this case the Al 3mo LME). This is due to the fact that premiums will be paid out by secondary producers regardless; in other words, if demand for the production of a specific alloy is high it can create a substantial demand for secondary scrap. Often, the question of whether investing in technology that can produce cleaner, more pure streams is a viable pursuit if it can only be afforded by a select few, but this indicates if increased demand for secondary materials continues to rise in the future, the result could be that such technologies would be economical to recyclers on a larger scale.

5.2 Key Takeaways

- When materials come out of stock, or are simply discarded for newer versions (whatever the case may be when they reach their end of life), they still contain a lot of value and to obtain that value safely and efficiently, there is much to be learned.
- Regardless of how many variables and parameters are evaluated, there will always be unknowns and unforeseen changes.
- Costs of downgrades and rejections have a significant impact on profit margins thus, putting the time and effort into preventing them is warranted.

- ISRI's code of conduct and the existence of defined commodities are ideal guidelines but not a full industry picture. Instruction only goes so far when operations are lacking the necessary tools to carry them out.
- Developing SOPs for this industry is going to be limited because everything entering the yard must be treated as unique and every yard receives different feeds of material.
- If other points along the supply chain incorporated end of life considerations into their processes, it would decrease the burden that currently falls heavily on recycling facilities.

5.3 Recommendations and Future Work

Although EOL is the focus of this work, applying systems thinking means understanding that all the other aspects of the supply chain are accountable points of impact on what happens to materials at their end of life and cannot be ignored. Throughout this research, it has been made clear that metal recyclers/scrap yards were not an industry established in order to assume the responsibility of handling mass volumes of mixed materials resulting from a make-take-waste societal mentality. As they are now the only systems in place that could potentially help in managing materials coming out of stock, they have been tasked with this unbalanced undertaking and therefore require areas of reform and additional support. This support is going to need to come from other points along the supply chain. The beginning, with product design and extended producer responsibility. The middle, with iterative education and research, and the end, in the form of advanced technologies. As we aim to improve the facilities responsible for waste management, recycling, and material recovery, we must understand how they operate and the current processes in place. Particularly, with ferrous and nonferrous metals, we can now see the roles that market conditions, logistics, commodity designations, equipment availability, and several other costs play in the decision making of the end-product. We have a better grasp on the gravity inbound inspection holds as a preventative measure to comingling, downcycling, and contamination build-up. The dangers and hazards have been accentuated, giving us a better grasp on what workers are met with every day when trying to handle materials. Safety should always be a top priority when evaluating processes, and the types of new technology and equipment to design and apply, for concerns exist at every stage in yard operations and extend to the customer after shipped.

There are costs to the environment and society if we continue to landfill and do not prioritize cleaner streams. Not only should considerations like these take precedence because large sums of energy go into producing goods, and being able to recover these materials helps in working toward a more circular economy, but trade relations are becoming increasingly fragile. Countries are rejecting and returning material deeming it too contaminated, climate change impacts can disrupt supply and the transportation of goods, the costs of producing primary materials will eventually soar, and the accumulation of impurities will impair future products. The techno-economic assessment comparing technologies of varying capabilities has shown us the conditions that make identification and sorting costly, and they are conditions that we can control to a degree. The more specific sorting at higher volumes is the better decision economically and supports what we need from the industry environmentally. In every market that was examined, this way of processing materials proved profitable, the variables that can drastically change this are downtimes, high error at low volumes, and safety issues. These dilemmas can be improved upon by continually investing in operations' efficiency and quick identification technology. In addition, we should further explore pre-processing technologies and capabilities, and work frequently to increase the durability of equipment and advancements in safety mechanisms.

One of the solutions to Climate Change is to invest, educate, and execute sustainable practices, which means recycling should only come as an attempt to intercept materials on their way to landfills after we have exhausted our efforts to reduce and reuse. With that in mind, we need to ensure that the industry responsible for doing the recycling has the tools and practices that are effective and efficient in getting materials identified and sorted to the best of their ability. The capacity to handle large mixed volumes quickly, with low error, high recovery rates, and at a price that is *affordable,* is the ultimate goal for technology in this industry. This research helps define where in fact we are in this endeavor, the operational processes that require more attention, the factors that influence how these processes are done, and the unique challenges to developing technology for this industry and improving these processes. In addition, this work not only explored the technologies that are being developed but quantified their value in comparison to one another, looking at parameters and considering variables that have not before been documented.

It is important to remember that the challenges of today, *can be* compounded tomorrow, and *will always be* continually changing; they will reflect new and developing societal principles and practices. What will end up in recycling facilities in the future? That picture isn't clear, but what we do know is that scrap yards will be faced with new, potentially dangerous contaminants and materials/situations that can cause fires and explosions; we are seeing a growing trend in this now as lithium-ion batteries become more commonplace. Another area that will alter operations, is the potential for the reconsideration of how items will be packaged and shipped, not just for sustainability reasons but because typical methods are inadequate. Gaylord boxes have been failing to properly contain their contents and often need to be reinforced, super sacks are becoming less popular, and baling materials makes it impossible to know if there are problem materials hidden in the middle. Then there is always the possibility of certain technologies we deem efficient now, growing and leading to unforeseen problems in the future. If we consider an increase in shredder activity, for instance, in its current form and with increased usage this technology will inevitably lead to a growth in ASR (or "fluff") production. This can be harmful to human health and the environment, as well as creating a considerable amount of landfill feed. Furthermore, we have yet to figure out best practices for the recycling of renewable energy technologies, such as photovoltaic (PV) cells, and end of life electric vehicles. Atop of all this, we expect swings in material demand and product designs. With these future considerations in mind, it is clear we need to continue to push for an increase in on-site technology research and improve collaboration between industry and academia. We must also keep striving for more transparency, education, and policy, as well as continuous discussions around circular economy, extended producer responsibility, product design, and design for recycling (DfR).

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Appendix A: Cost Benefit Analysis Models

Modeling done in excel for each technique at max capacity in Market 1.

Scenario A – Hand Sorting, Comingled @ 660,000 lbs/mo

	A	B	C	D	E	F	G	H
1		Date: ______________	Market:	Feb2020 3 mo LME Al ($/Lb)	0.776	________ Pb ($/Lb)		
2				________ AMM Fe ($/Lb)		________ Ni ($/Lb)		
3				Mar20 ________ Cmx Cu ($/Lb)	2.587	________ Zn ($/Lb)		
4	Product Information	Equipment Manufacture & Model (or Method of Sort)	As Is by Hand					
5		What does it offer (specifications, size tolerance, etc.)	Minimal Equipment Costs, Minimal Knowledge, High Speed Hand Sorting					
6		What material are you evaluating its efficacy on	be free of 2xxx and 7xxx series, hair wire, wire screen, punchings less 1/2" diameter, dirt, and other non-metallic items. Grease and oil not to total more than					
7		What package are you trying to improve	MLC (Mixed Low Copper Aluminum Clippings and Solids)					
8		What commodities do you intend to sort	Nonmetallics from MLC					
9		Scenario	Dump, pick up throw in a hopper, forklift comes over when hopper is full, dumps in roll-off, and returns hopper. 2 hoppers					
10			there so no lag time in sorting					
11		Capacity (per person)	1,500.00		lbs/hr	0.75		tons/hr
12								
13	Parameter Variables	Capacity (per mo) = total lbs/shift * # of shifts	660,000.00		Lbs/mo			
14		Expected Volume (Lbs/mo)	660,000		Lbs/mo	294.64		GT
15		Expected Volume (Lbs/mo) less 1% contamination	653,400.0		Lbs/mo			
16								
17		Inspector/Supervisor						
18			2	# of Laborers				
19		Hand Labor	50	pcs/min	2	pcs=lb	25.00	lbs/min
20			15000	lbs/person/shift	30000	total lbs/shift		
21								
22								
23								
24								
25	Direct (Operations) Productivity	Processing (Lbs/mo)	660,000		Lbs/mo			
26		Labor hours (per person)	220.00		Hrs	440	220	
27		Cumulative needed to process expected volume (Hrs)	440.00		Hrs			
28		1 shift	10		Hrs			
29		# of shifts worked per month	22		Shifts			
30		# of available hours for processing	220		Hrs			
31								
32								
33	Direct (Operations) Additional Equipment Costs		Depreciation/Mo (7* years straight line)			Cost	Quantity	
34		Front Loader	$	-				
35		Forklift	$	535.71	$	45,000.00	1	
36								
37		Total Additional Equipment Costs	$	535.71				
38		Total Additional Equipment Costs/lb	$	0.0008				

	A	B	C	D	E	F	G	H	I	J
40										
41	Direct (Operations) Labor Costs	Laborer/HH Operator	2	# of operator(s)	13.5	$/hr	220.00	Hrs	$ 5,940.00	$/mo
42		Forklift/Skid Steer Operator	1	# of operator(s)	15	$/hr	22.00	Hrs	$ 330.00	$/mo
43		Front Loader Operator	0	# of operator(s)	19	$/hr		Hrs	$ -	$/mo
44		Additional Laborers		# of laborer(s)		$/hr		Hrs		$/mo
45		Inspector/Supervisor	0	# of inspector(s)	25	$/hr	0.00	Hrs	$ -	$/mo
46		Total Labor Costs	$						6,270.00	$/mo
47		Total Labor Costs	$						0.0095	$/lb/mo
48										
49	Additional & Indirect Costs	Additional Freight Charges: Underweight penalty ($/lb)	$ 0.01	Every 10K under 40K = .01	5-10K	10-20k	20-30k	30-40k		
50					0.04	0.03	0.02	0.01		
51		Overhead (rent, utilities, insurance)	$ 0.01							
52		Maintenance Costs (lbs/mo)								
53		Total Indirect Costs	$ 0.02							
54										
55										
56	Purchasing		$/lb (del)	Total Purchase Cost	lbs	approx tipping fee per lb	additional $ lost			
57		Al MLC	$ 0.380	$ 250,800.00						
58		dirt, moisture, non-metallics cost	$ (0.38)	$ (2,508.00)	(6,600.00)	$ 0.04	$ (264.00000)			
59		Adjusted Price	$ 0.384	$ 251,064.00						
60										
61			$/lb (Del)	Expected Volume %	Total Lbs	$/mo	Weighted value/lb	Profit Margin		
62	Sale	Al MLC - "As is" scenario	0.480	100%	653400	$ 313,632.000	$ 0.480	$ 0.096		
63										
64										
65										
66										
67										
68	Summary	Gross: As Is	$	313,632.00						
69		Costs for operating volume received	$	0.0303						
70		Total Costs as applied to actual lbs sold (including purchase cost)	$	270,869.657	$ 0.41					
71		Profit/lb	$	0.096						
72		Profit less costs per lb	$	0.06545						
73		As Is - Costs	$	42,762.343	$ 0.06545	the difference between c70 and gross = profit				
74		[Profit less costs per lb]*actual shipped weight	$	42,762.34						
75										
76		Actual Purchase Price	$ 0.41							
77										
78										
79										
80	Checks			$ 0.065	$ 0.0303					
81		Costs = Actual Purchase Price - Adjusted Purchase Price	$ 0.0303			$ 42,762.34				
82		Sale Price - [Profit less costs per lb]	$ 0.41							
83		Sale Price - [actual purchase price]	$ 0.065							
84		(A) Profit per lb * actual shipped weight	$ 62,568.00	$ 0.065446						
85		(B) Operating costs for volume received * actual shipped weight	$ 19,805.66							
86		A-B	$ 42,762.34							
87										

Scenario B – Hand Sorting, Sort out 6063 @ 594,000 lbs/mo

	A	B	C	D	E	F	G	H
1		Date: ________________	Market:	Feb2020 3 mo LME /	0.776	__________Pb ($/Lb)		
2				__________ AMM Fe ($/Lb)		__________Ni ($/Lb)		
3				Mar20 __________ Cmx (	2.587	__________Zn ($/Lb)		
4	Product Information	Equipment Manufacture & Model (or Method of Sort)	As Is by Hand					
5		What does it offer (specifications, size tolerance, etc.)	Minimal Equipment Costs, Minimal Knowledge, High Speed Hand Sorting					
6		What material are you evaluating its efficacy on	Aluminum MLC ISRI Spec: New, clean, uncoated and unpainted low copper aluminum scrap of two or more alloys with a minimum thickness of 0.015" and to be free of 2xxx and 7xxx series, hair wire, wire screen, punchings less 1/2" diameter, dirt, and other non-metallic items. Grease and oil not to total more than 1% Variations to this specification should be agreed upon prior to shipment between buyer and seller.					
7		What package are you trying to improve	MLC (Mixed Low Copper Aluminum Clippings and Solids)					
8		What commodities do you intend to sort	Nonmetallics from MLC					
9		Scenario	Dump, pick up throw in a hopper, forklift comes over when hopper is full, dumps in roll-off, and returns hopper. 4 hoppers there so no lag time in sorting. Sorting out 1 additional alloy (6063) from MLC. Only minor lag, grab all 63 see and then move on to mlc					
10								
11		Capacity (per person)	1,350.00		lbs/hr	0.675		tons/hr
12								
13	Parameter Variables	Capacity = total lbs/shift * # of shifts	594,000.00					
14		Expected Volume (Lbs/mo)	594,000		Lbs/mo	265.18		GT
15		Expected Volume (Lbs/mo) less 1% contamination	588,060		Lbs/mo			
16								
17		Inspector/Supervisor						
18			2	# of Laborers				
19		Hand Labor	45	pcs/min	2	pcs=lb	22.50	lbs/min
20			13500	bs/person/shif	27000	total lbs/shift		
21								
22								
23								
24								
25	Direct (Operations) Productivity	Processing Volume (Lbs/mo)	594,000		Hrs			
26		Labor hours (per person)	220.00		Hrs			
27		Cumulative needed to process expected volume (Hrs)	440.00		Hrs	440		
28		1 shift	10		Hrs			
29		# of shifts worked per month	22		Shifts			
30		# of available hours for processing	220		Hrs			
31								
32								
33	Direct (Operations) Additional Equipment Costs		epreciation/Mo (7* years straight lir			Cost	Quantity	
34		Front Loader	$	-				
35		Forklift	$	535.71	$	45,000.00	1	
36								
37		Total Additional Equipment Costs	$	535.71				
38		Total Additional Equipment Costs/lb	$	0.0009				
39								

	A	B	C	D	E	F	G	H	I	J
40										
41	Direct (Operations) Labor Costs	Laborer/HH Operator	2	# of operator(s)	13.5	$/hr	220.00	Hrs	$ 5,940.00	$/mo
42		Forklift/Skid Steer Operator	1	# of operator(s)	15	$/hr	22.00	Hrs	$ 330.00	$/mo
43		Front Loader Operator	0	# of operator(s)	19	$/hr		Hrs	$ -	$/mo
44		Additional Laborers		# of laborer(s)		$/hr		Hrs		$/mo
45		Inspector/Supervisor	0	# of inspector(s)	25	$/hr	0.00	Hrs	$ -	$/mo
46		Total Labor Costs	$						6,270.00	$/mo
47		Total Labor Costs	$						0.0106	$/lb/mo
48										
49	Additional & Indirect Costs	Additional Freight Charges: Underweight penalty ($/lb)	$ 0.01	Every 10K under	5-10K	10-20k	20-30k	30-40k		
50				40K = .01	0.04	0.03	0.02	0.01		
51		Overhead (rent, utilities, insurance)	$ 0.01							
52										
53		Total Indirect Costs	$ 0.05							
54										
55										
56	Purchasing		$/lb (del)	Total Purchase C	lbs	approx tipping fee per lb	additional $ lost			
57		Al MLC	$ 0.38	$ 225,720.00						
58		dirt, moisture, non-metallics cost	$ (0.38)	$ (2,257.20)	(5,940.00)	$ 0.04	$ (237.60000)			
59		Adjusted Price	$ 0.384	$ 225,957.60						
60										
61			$/lb (Del)	Expected Volume %	Total Lbs	$/mo	Weighted value/lb	Profit Margin		
62	Sale	Al MLC	0.480	69%	######	$ 194,765.472	$ 0.331			
63		Al 6063	0.7	31%	182,299	$ 127,609.020	$ 0.217			
64										
65				100%		$ 322,374.49	$ 0.55	$ 0.164		
66										
67										
68	Summary	Gross	$ 322,374.49							
69		Costs for operating volume received	$ 0.0615							
70		Total Costs as applied to actual lbs sold (including purchase cost)	$ 262,098.257							
71		Profit/lb	$ 0.164							
72		Profit less costs per lb	$ 0.1025							
73		Gross - Costs	$ 60,276.235							
74		[Profit less costs per lb]* actual shipped weight	$ 60,276.23							
75										
76		Actual Purchase Price	$ 0.45							
77										
78										
79										
80				$ (0.11)						
81	Checks	Costs = Actual Purchase Price - Adjusted Purchase Price	$ 0.0615			$ 60,276.23				
82		Sale Price - [Profit less costs per lb]	$ 0.45							
83		Sale Price - [actual purchase price]	$ 0.1025							
84		(A) Profit per lb * actual shipped weight	$ 96,416.89	$ 0.102500						
85		(B) Operating costs for volume received * actual shipped weight	$ 36,140.66							
86		A-B	$ 60,276.23							
87										

Scenario C – Hand Sorting, specific sort with Handheld Analyzers @ 495,000 lbs/mo

	A	B	C	D	E	F	G	H
1		Date: ____________	Market:	Feb2020 3 mo LME A	0.776	__________Pb ($/Lb)		
2				__________ AMM Fe ($/Lb)		__________Ni ($/Lb)		
3				Mar20 ______ Cmx C	2.587	__________Zn ($/Lb)		
4	Product Information	Equipment Manufacture & Model				As Is by Hand		
5		What does it offer (specifications, size tolerance, etc.)						
6		What material are you evaluating its efficacy on						
7		What package are you trying to improve						
8		What commodities do you intend to sort						
9		Scenario	Dump, pick up throw in a hopper, forklift comes over when hopper is full, dumps in roll-off, and returns hopper. 8 hoppers (2 for 63 &61) there so no lag time in sorting. Sorting out 6 total commodities.					
10								
11		Capacity (per person)	750.00		lbs/hr	0.375		tons/hr
12								
13	Parameter Variables	Capacity = total lbs/shift * # of shifts	495,000.00		Hrs			
14		Expected Volume (Lbs/mo)	495,000		Lbs/mo	220.98		GT
15		Expected Volume (Lbs/mo) less 1% contamination	490,050		Lbs/mo			
16		Percent Error (comingled)	5%		MLC			
17		Inspector/Supervisor	1					
18			2	# of Laborers				
19		Processing by HH Operators	25	pcs/min	2	pcs=lb	12.50	lbs/min
20			7500	bs/person/shif	22500	total lbs/shift		
21								
22								
23								
24								
25	Direct (Operations) Productivity	Processing Volume (Lbs/mo)	495,000		Lbs/mo			
26		Labor hours (per person)	220.00		Hrs			
27		Cumulative needed to process expected volume (Hrs)	660.00		Hrs			
28		1 shift	10		Hrs			
29		# of shifts worked per month	22		Shifts			
30		# of available hours for processing	220		Hrs			
31								
32								
33	Direct Physical [Product] Costs	Equipment Cost (baseline) ($)	$	30,000.00				
34		Number of Instruments	$	2.00				
35		Total Cost ($)	$	60,000.00				
36		1 yr payment plan $/mo	$	5,000.00				
37		Total Cost (w/Depreciation) ($/lb)	$	0.0102				
38								
39								
40	Direct (Operations) Additional Equipment Costs		epreciation/Mo (7" years straight lir			Cost	Quantity	
41		Front Loader	$	-				
42		Forklift	$	535.71	$	45,000.00	1	
43								
44		Total Additional Equipment Costs	$	535.71				
45		Total Additional Equipment Costs/lb	$	0.0011				

	A	B	C	D	E	F	G	H	I	J
46										
47										
48	Direct (Operations) Labor Costs	Laborer/HH Operator	2	# of operator(s)	13.5	$/hr	220.00	Hrs	$ 5,940.00	$/mo
49		Forklift/Skid Steer Operator	1	# of operator(s)	15	$/hr	22.00	Hrs	$ 330.00	$/mo
50		Front Loader Operator	0	# of operator(s)	19	$/hr		Hrs	$ -	$/mo t
51		Additional Laborers		# of laborer(s)		$/hr		Hrs		$/mo
52		Inspector/Supervisor	1	# of inspector(s)	25	$/hr	220.00	Hrs	$ 5,500.00	$/mo
53		Total Labor Costs	$						11,770.00	$/mo
54		Total Labor Costs	$						0.0238	$/lb/mo
55										
56	Additional & Indirect Costs	Additional Freight Charges: Underweight penalty ($/lb)	$ 0.01	Every 10K under	5-10K	10-20k	20-30k	30-40k		
57				40K = .01	0.04	0.03	0.02	0.01		
58		Overhead (rent, utilities, insurance)	$ 0.01							
59		Maintenance Costs (lbs/mo)								
60		Total Indirect Costs	$ 0.03							
61										
62										
63	Purchasing		$/lb (del)	Total Purchase C	lbs	approx tipping fee per lb	additional $ lost			
64		Al MLC	$ 0.3800	$ 188,100.00						
65		dirt, moisture, non-metallics cost	$ (0.38)	$ (1,881.00)	(4,950.00)	$ 0.04	$ (198.00)			
66		Adjusted Price	$ 0.384	$ 188,298.00						
67										
68			$/lb (Del)	Expected Volume %	Total Lbs	$/mo	Weighted value/lb	Profit Margin		
69	Sale	Al MLC (Error %)	0.480	5%	24,502.50	$ 11,761.200	$ 0.024			
70		Al - Misc 5xxx	0.615	12%	58806	$ 36,165.69	$ 0.07			
71		Al - 5052	0.718	18%	88209	$ 63,345.09	$ 0.13			
72		Al - Misc 6xxx	0.64	11%	53905.5	$ 34,499.52	$ 0.07			
73		Al - 6061	0.610	23%	112711.5	$ 68,754.02	$ 0.14			
74		Al - 6063	0.700	31%	151915.5	$ 106,340.85	$ 0.22			
75				100%	490,050.00	$ 320,866.36	$ 0.65	$ 0.271		
76										
77										
78	Summary	Gross	$	320,866.36						
79		Costs for operating volume received	$	0.0549						
80		Total Costs as applied to actual lbs sold (including purchase cost)	$	215,182.157						
81		Profit/lb	$	0.271						
82		Profit less costs per lb	$	0.2157						
83		Gross - Costs	$	105,684.206						
84		[Profit less costs per lb]* actual shipped weight	$	105,684.21						
85										
86		Actual Purchase Price	$ 0.44							
87										
88										
89										
90				$ (0.42)						
91	Checks	Costs = Actual Purchase Price - Adjusted Purchase Price	$ 0.0549			$ 105,684.21				
92		Sale Price - [Profit less costs per lb]	$ 0.44							
93		Sale Price - [actual purchase price]	$ 0.2157							
94		(A) Profit per lb * actual shipped weight	$ 132,568.36	$ 0.215660						
95		(B) Operating costs for volume received * actual shipped weight	$ 26,884.16							
96		A-B	$ 105,684.21							

Scenario D - Steinert @ 880,000 lbs/mo

	A	B	C	D	E	F	G	H
1		Date: ________________	Market:	Feb2020 3 mo LME Al ($/Lb)	0.776	________Pb ($/Lb)		
2				__________ AMM Fe ($/Lb)		________Ni ($/Lb)		
3				__________ Cmx Cu ($/Lb)		________Zn ($/Lb)		
4	Product Information	Equipment Manufacture & Model	Steinert LSS | LIBS					
5		What does it offer (specifications, size tolerance, etc.)	Sort Al by alloy type including 5xxx from 6xxx					
6		What material are you evaluating its efficacy on	Aluminum					
7		What package are you trying to improve	MLC					
8		What commodities do you intend to sort	5xxx, 6xxx					
9		Scenario						
10		Capacity (lbs per hour)	4000		lbs/hr	2		tons/hr
11								
12	Parameter Variables	Capacity = total lbs/shift * # of shifts	880,000.00		Hrs			
13		Expected Volume (Lbs/mo)	880,000		Lbs/mo	392.86		GT
14		Expected Volume (Lbs/mo) less 1% contamination	871,200		Lbs/mo			
15		Percent Error	10%					
16								
17								
18								
19								
20	Direct Physical [Product] Costs	Equipment Cost (baseline) ($)	$	1,000,000.00				
21		Install Cost ($)	$	250,000.00				
22		Total Cost ($)	$	1,250,000.00				
23		Depreciation/mo (7* years straight line)	$	14,880.95				
24		Total Cost (w/Depreciation) ($/lb)	$	0.017				
25								
26								
27								
28	Direct (Operations) Productivity	Processing (Lbs/mo)	880,000		Lbs/mo			
29		Processing (Lbs/hr)	4000		Lbs/hr			
30		Hours needed to process expected volume (Hrs)	220		Hrs			
31		1 shift	10		Hrs			
32		# of shifts worked per month	22		Shifts			
33		# of available hours for processing	220		Hrs			
34								
35			Depreciation/Mo (7* years straight line)		Cost		Quantity	
36	Direct (Operations) Additional Equipment Costs	Front Loader	$	5,952.38	$	500,000.00	2	
37		Forklift	$	535.71	$	45,000.00		
38								
39		Total Additional Equipment Costs	$	6,488.10	$	545,000.00		
40		Total Additional Equipment Costs/lb	$	0.007				
41								
42								
43	Direct (Operations) Labor Costs	Stienert Operator	1	# of operator(s)	20	$/hr	$4,400.00	$/mo
44		Forklift/Skid Steer Operator	1	# of operator(s)	15	$/hr	$3,300.00	$/mo
45		Front Loader Operator	2	# of operator(s)	19	$/hr	$8,360.00	$/mo
46		Additional Laborers		# of laborer(s)		$/hr		$/mo
47		Inspector/Supervisor		# of supervisor(s)		$/hr		$/mo
48		Total Labor Costs	$				16,060.00	$/mo
49		Total Labor Costs	$				0.018	$/lb/mo

	A	B	C	D	E	F	G	H
51								
52	Additional & Indirect Costs	Additional Freight Charges: Underweight penalty ($/lb)	$ 0.01	Every 10K under 40K = .01	5-10K	10-20k	20-30k	30-40k
53					0.04	0.03	0.02	0.01
54		Overhead (rent, utilities, insurance)	0.01					
55		Maintenance Costs (lbs/mo)						
56		Total Indirect Costs	$ 0.02					
57								
58								
59	Purchasing		$/lb (del)	Total Purchase Cost	lbs	approx tipping fee pe	additional $ lost	
60		Al MLC	$ 0.3800	$ 334,400.00				
61		dirt, moisture, non-metallics cost	$ (0.38)	$ (3,344.00)	(8,800.00)	$ 0.04	$ (352.00)	
62		Adjusted Price	$ 0.3842	$ 334,752.00				
63								
64								
65	Commodity Pricing		$/lb (p/u)	Expected Volume %	Total Lbs	$/mo	Weighted value/lb	Profit Margin
66								
67		Al - Misc 5xxx	$ 0.615	11%	95832	$ 58,936.68	$ 0.07	
68		Al - 5052	$ 0.718	17%	148104	$ 106,357.19	$ 0.12	
69		Al - Misc 6xxx	$ 0.640	10%	87120	$ 55,756.80	$ 0.06	
70		Al - 6061	$ 0.610	22%	191664	$ 116,915.04	$ 0.13	
71		Al - 6063	$ 0.700	30%	261360	$ 182,952.00	$ 0.21	
72		Al MLC	$ 0.483	10%	87120	$ 42,078.96	$ 0.05	
73		Total Sorted Gross		100%	871200	$ 562,996.67	$ 0.646	$0.262
74								
75								
76	Summary	Gross	$	562,996.67				
77		Costs for operating volume received	$	0.0625				
78		Total Costs as applied to actual lbs sold (including purch	$	389,230.757				
79		Profit/lb	$	0.262				
80		Profit less costs per lb	$	0.1995				
81		Gross - Costs	$	173,765.908				
82		[Profit less costs per lb]* actual shipped weight	$	173,765.91				
83								
84		Actual Purchase Price	$ 0.447					
85								
86								
87								
88								
89	Checks	Price	$ 0.0625					
90		Sale Price - [Profit less costs per lb]	$ 0.447					
91		Sale Price - [actual purchase price]	$ 0.1995					
92		(A) Profit per lb * actual shipped weight	$ 228,244.67	$ 0.197461				
93		(B) Operating costs for volume received * actual shippec	$ 54,478.76					
94		A-B	$ 173,765.91					
95								
96			Total Equip Costs	Profit /mo	Months	Years		
97	ROI	max capacity (880K lbs/mo)	$ 1,795,000.00	$ 173,765.91	10.33	0.8608		
98		lowest capacity (100k lbs/mo)	$ 1,795,000.00	$ 994.79	1804.40	150.367		
99		7 year *194k lbs/mo	$ 1,795,000.00	$ 21,815.92	82.28	6.857		

Scenario E – High Capacity Shredder @ 880,000 lbs/mo 13,200,000 lbs/mo

	A	B	C	D	E	F	G	H
1		Date: ______________	Market:	Feb2020 3 mo LME Al ($/L	0.776	________Pb ($/Lb)		
2				________AMM Fe ($/Lb)		________Ni ($/Lb)		
3				________Cmx Cu ($/Lb)		________Zn ($/Lb)		
4	Product Information	Equipment Manufacture & Model			High Capacity Shredder			
5		What does it offer (specifications, size tolerance, etc.)			Process Increased Volume			
6		What material are you evaluating its efficacy on			Fe			
7		What package are you trying to improve			Zorba			
8		What commodities do you intend to sort			Metallics from Non Metallics			
9		Capacity (lbs)			13,200,000.00			
10								
11								
12	Parameter Variables	Expected Volume (Lbs/mo)	13,200,000		Lbs/mo	5892.86		GT
13		Expected Volume (Lbs/mo) less 1% contamination	13,068,000		Lbs/mo			
14		Percent Error	10%					
15								
16								
17								
18								
19	Direct Physical [Product] Costs	Equipment Cost (baseline) ($)	$	2,400,000.00				
20		Install Cost ($)	$	375,000.00				
21		Total Cost ($)	$	2,775,000.00				
22		Depreciation/mo (7* years straight line)	$	33,035.71				
23		Total Cost (w/Depreciation) ($/lb)	$	0.003				
24								
25								
26								
27	Direct [Operations] Productivity	Processing (Lbs/mo)	13,200,000		Lbs/mo			
28		Processing (Lbs/hr)	60000		Lbs/hr			
29		Hours needed to process expected volume (Hrs)	220		Hrs			
30		1 shift	10		Hrs			
31		# of shifts worked per month	22		Shifts			
32		# of available hours for processing	220		Hrs			
33								

	A	B	C	D	E	F	G	H
34								
35			Depreciation/Mo (7* years straight		Cost		Quantity	
36	Direct [Operations] Additional Equipment Costs	Front Loader	$	5,952.38	$	500,000.00	2	
37		Forklift	$	535.71	$	45,000.00	1	
38		Transportation/Trucking (Freight)						
39		Total Additional Equipment Costs	$	6,488.10	$	545,000.00		
40		Total Additional Equipment Costs/lb	$	0.000				
41								
42								
43	Direct [Operations] Labor Costs	Stienert Operator	1	# of operator(s)	20	$/hr	$ 4,400.00	$/mo
44		Forklift/Skid Steer Operator	1	# of operator(s)	15	$/hr	$ 3,300.00	$/mo
45		Front Loader Operator	2	# of operator(s)	19	$/hr	$ 8,360.00	$/mo
46		Additional Laborers		# of laborer(s)		$/hr		$/mo
47		Inspector/Supervisor		# of supervisor(s)		$/hr		$/mo
48		Total Labor Costs	$				16,060.00	$/hr/mo
49		Total Labor Costs	$				0.001	$/lb/mo
50								
51								
52	Additional & Indirect Costs	Additional Freight Charges: Underweight penalty ($/lb)	-	Every 10K under 40K	5-10K	10-20k	20-30k	30-40k
53				= .01	0.04	0.03	0.02	0.01
54		Overhead (rent, utilities, insurance)	0.01					
55		Maintenance Costs (lbs/mo)						
56		Total Indirect Costs	$ 0.01					
57								
58								
59	Purchasing		$/lb (del)	Total Purchase Cost	lbs	approx tipping fee	additional $ lost	
60		Fe Shred	$ 0.0300	$ 396,000.00				
61		dirt, moisture, non-metallics cost	$ (0.030)	$ (3,960.00)	(132,000.00)	$ 0.04	$ (5,280.00)	
62		Adjusted Price	$ 0.0307	$ 401,280.00				
63								
64								
65	Commodity Pricing		$/lb (p/u)	Expected Volume %	Total Lbs	$/mo	Weighted value/lb	Profit Margin
66								
67			$ -	0%	0	$ -	$ -	
68			$ -	0%	0	$ -	$ -	
69			$ -	0%	0	$ -	$ -	
70			$ -	0%	0	$ -	$ -	
71		Metallics	$ 0.080	90%	11761200	$ 940,896.00	$ 0.07	
72		Nonmetallics	$ (0.050)	10%	1306800	$ (65,340.00)	$ (0.01)	
73		Total Sorted Gross		100%	13068000	$ 875,556.00	$ 0.067	$ 0.036
74								
75								
76	Summary	Gross	$	875,556.00				
77		Costs for operating volume received	$	0.0142				
78		Total Costs as applied to actual lbs sold (including purchas	$	586,987.971				
79		Profit/lb	$	0.036				
80		Profit less costs per lb	$	0.0221				
81		Gross - Costs	$	288,568.029				
82		[Profit less costs per lb]*actual shipped weight	$	288,568.03				
83								
84		Actual Purchase Price	$ 0.045					
85								
86								
87								
88				$ (0.04)				
89	Checks	Costs = Actual Purchase Price - Adjusted Purchase Price	$ 0.0142					
90		Sale Price - [Profit less costs per lb]	$ 0.045					
91		Sale Price - [actual purchase price]	$ 0.0221					
92		(A) Profit per lb * actual shipped weight	$ 474,276.00	$ 0.021861				
93		(B) Operating costs for volume received * actual shipped we	$ 185,707.97					
94		A-B	$ 288,568.03					